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# SYNOPTIC-AEROLOGICAL INVESTIGATION OF WEATHER CONDITIONS IN EUROPE, 17—24 APRIL 1939

BY

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# SYNOPTIC-AEROLOGICAL INVESTIGATION OF WEATHER CONDITIONS IN EUROPE, 17—24 APRIL 1939.

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IN THE PHYSICAL LECTURE THEATRE,
FEBRUARY 10TH. 1945 AT 10 O'CLOCK,
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OF PHILOSOPHY

BY

ALF NYBERG
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# SYNOPTIC-AEROLOGICAL INVESTIGATION OF WEATHER CONDITIONS IN EUROPE, 17—24 APRIL 1939.

By *A. NYBERG.*

## PREFACE.

Scientific synoptic meteorology operates to a large degree in the same way as the practical meteorological service. It is one of the aims of this science to develop the working methods of the weather service and increase the reliability and range of the prognoses in time and space. Another purpose of scientific synoptic meteorology is to obtain information and knowledge about everything that occurs in the atmosphere under all the changing conditions of the weather. This knowledge, of course, leads indirectly to practical results.

As in the case of other branches of science, synoptic meteorology has secured certain ground through theoretical work and empirical investigations, but it is still to a very large extent unestablished. It is true that theorists, assuming simplified conditions, have solved many atmospherical problems, but the complex character of the atmosphere necessitates extensive empirical research work in order to test the validity of assumptions made, and thus also the applicability of the theories. True knowledge of atmospherical conditions is of course in the first place to be gained through aerological observations. Aerological synoptics, however, has great difficulties to overcome. The meteorological instruments which can be used in a synoptic-aerological investigation are insufficient and defective. As a rule the vertical movements of the air cannot be directly measured; its horizontal movements can, in certain cases, be estimated, but not with sufficient accuracy. The humidity is difficult to determine, and thermometers and barometers are not accurate enough for all purposes. These instrumental defects must be taken into consideration when synoptic-aerological investigations are being made, as they may lead to completely incorrect conclusions. A critical examination of the data obtained from observations is therefore one of the first conditions to be fulfilled if an investigation is to give increased knowledge of atmospherical conditions.

In new investigations typical cases can be chosen. In doing this a selection is made, which does not prevent many general conclusions from being reached. They must, however, be supplemented by investigations for which no special conditions have been chosen, such as the present one, selected only with regard to the comparatively plentiful material during the week 17—22 April 1939.

Considering the influential position of the Norwegian meteorological school within the modern meteorological service, and the conclusions which have been reached in previous synoptic-aerological investigations, it is only natural that the Norwegian ideas

have been allowed to lead the way in the present investigation. The author has, however, tried to avoid an uncritical application of these ideas. It is true that the character of air movements makes it possible to use certain patterns for superficial investigations, but a more precise analysis clearly reveals the defects of a pattern. One of the aims of aerological synoptics must be to examine critically the old patterns and to obtain material which can improve them.

Within the sphere of synoptic-aerological meteorology there are many problems which are as yet unsolved. The author has treated several of these, such as the significance, formations and changes of air masses and fronts, cyclogenesis and occlusion and, connected with this, vertical and horizontal movements of air. Further, accelerations and deviations from the geostrophic wind (divergence-convergence effects), the formation of precipitation through upward gliding along a front and through elevation or instability on account of the different velocities of the various layers of air. These and other problems have been subjected to many theoretical and empirical investigations which have clarified obscure points. It is difficult to obtain satisfactory knowledge from the material now available to aerologists, but apparently it is only through synoptic-aerological investigations that further progress can be made, even if this method is laborious and slow. For this reason the author has, on the basis of relatively abundant material, endeavoured to scrutinize previously reached conclusions and to present new points of view on the phenomena observed. Thus the present work is intended as a contribution to the larger investigation of atmospherical circulation problems carried on by many meteorologists at the present moment.

This investigation has been carried out with the assistance of many institutions and private persons whom the author has the pleasurable duty of thanking. Copies have kindly been put at the author's disposal by the Danish Meteorological Institute, Copenhagen, the Norwegian Meteorological Institute, Oslo, the Finnish Meteorological Institute, Helsingfors, and the Secretariate of the International Meteorological Organisation, Lausanne. Special information has been obtained from the Secretariate of the International Aerological Commission, Berlin, and from the Meteorological Office, London.

The Meteorological-Hydrological Institute of Sweden (Statens Meteorologisk-hydrografiska Anstalt), Stockholm, has set at my disposal all its resources; I have been permitted to devote part of my official time to this work, and technical help has to a large extent been made available by the Institute. For the assistance rendered, without which the execution of this work in its present form would not have been possible, I wish to express my sincere thanks to the Director of the Institute, Överdirektör G. Slettenmark, and to Byrådirektör A. Ångström. Thanks are also extended to the technical staff of the Institute for their excellent work, especially in regard to the illustrated material which is presented with this thesis. Thanks to a grant from the Längmanska Kulturfonden, I have been enabled to have some diagrams drawn by the Office of the Swedish Ordnance Survey, and for advice and collaboration in this connection I wish to thank Byråchef N. O. Olsson. Thanks are also due to the British Council for a grant making this translation of my original manuscript possible and to Dr D. F. Cheesman for carry-

ing out the work of translation. In the translation use has been made of the meteorological dictionary by T. Bergeron printed in the »Meteorologisches Taschenbuch». Linke (1939).[1]

It has been of great help to me to have this work printed in the Geografiska Annaler. For this privilege I wish to tender my warmest gratitude to Svenska Sällskapet för Antropologi och Geografi.

I am greatly indebted to Prof. E. Palmén, Helsingfors, who has introduced aerological synoptics to me and who has from time to time during the course of this investigation given me valuable advice and shown an interest in the progress of the work which has been most stimulating.

Stockholm, August, 1944.

*A. N.*

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# INTRODUCTION.

Investigations of weather conditions have been carried out in a great number of cases ever since Brandes drew his first weather map in 1816. Since then synoptic ground maps have changed in many ways, mainly because observations have become more numerous, and because at the time of Brandes they only included pressure and wind direction, whereas now their range is large, as can be seen from the published maps.

The charts have also changed through the methods of analysis. The first weather forecasts based on synoptics were issued after studies of atmospheric pressure distribution. This isobarical method was developed by, among others, Ekholm and Jansson (1891 and 1907), who introduced the study of pressure changes with the aid of isallobars. After Margules (1905) had treated the problem of the source of energy of storms and v. Ficker (1910) had shown that North Asiatic cold spells and heat waves are of great significance in the development of depressions, V. Bjerknes and his collaborators[1] introduced a new synoptical method. They returned to ideas which had been presented by earlier research workers, among whom may be mentioned the German meteorologists Dove (1840) and Blasius (1875), the Englishmen Fitz-Roy (1863) and Shaw (1903 and 1906), clarifying and developing these ideas. This new method has been generally accepted by the meteorological bureaux of various countries. The purpose of modern synoptics is firstly to determine the condition of air masses and the fronts separating them, and then to follow their movements and study the change in their properties. Studies of ground observations and the use of so-called indirect aerology (Bergeron 1928) in ground synoptic investigations already gave results which seemed to confirm the theoretical expectations. Only through direct investigations of wind, temperature and humidity in air layers at high levels, however, could the correctness of numerous theories and hypotheses be tested.

Aerological investigations demand methods by which high layers of air can be technically examined, and this was made possible by the invention of the balloon. However, balloons were not effectively made use of for measurements of temperature until the latter part of the nineteenth century, when they were used in the first place by Glaisher (1862) and somewhat later by Assmann (1900 and 1902), and Teisserenc de Bort (1902). In 1902 the two latter discovered the isothermic stratosphere. It is also worth mentioning Hermite (1892), whose method of sending up unmanned registering balloons has been of the greatest significance to progress, as it cheapened the ascents and thus brought about an increase in the number of observations. For the same reason W. H. Dines (1909) and Jaumotte (1930) may be mentioned as the constructors of light meteorographs, and Rotch (1897) for his kite construction. In the beginning the results attained by aerological ascents were of general aerological and climatic interest. Synoptic aerological investigations were not commenced until aeroplanes could be used for simultaneous ascents from

[1] Many of the works of these scientists are to be found in the bibliography under the names: V. Bjerknes, J. Bjerknes, T. Bergeron, E. Calwagen, S. P. Chromow, J. Van Mieghem, E. Palmén, H. Solberg.

several stations. To start with, the area which could be made use of was often fairly limited and had only a few stations. Among early research workers in this field Douglas (1921 and later) is the most prominent. Thanks to his direct observations from aeroplanes important facts about the upper layers of the atmosphere have been obtained.

The aeroplanes hardly reached a height of more than 5 000 metres, but were supplemented by sounding balloon stations. Of great importance was the international collaboration which led to the introduction of so-called aerological months, weeks and days, when aerological surveys — which otherwise for economic reasons had to be strictly limited — were intensified to the greatest possible degree.

A fruitful collaboration was started in 1928 between J. Bjerknes, Bergen, and J. Jaumotte, Brussels; the latter supplied sondes of his own construction, so that series of ascents could be undertaken at Uccle near Brussels, and later on at Aas in the South of Norway, at each place with only a few hours interval.

At Uccle alone the following series of ascents took place:

1. Series of 28—30 March 1928 (7 sondes). Published by J. Bjerknes (1932), J. Bjerknes and E. Palmén (1934).

2. Series of 26—28 December 1928 (20 sondes). J. Bjerknes (1932).

3. Series of 24—26 November 1929 (34 sondes). Unpublished.

4. Series of 30—31 December 1930 (38 sondes). J. Bjerknes (1935).

The analysis was based on the synoptical ground chart and on vertical 'time-sections' which could be drawn assuming that the west to east disturbances which were being investigated moved with a constant velocity and did not change with time. Thus the time-sections replaced the sections in space.

5. The collaboration between Bjerknes and Jaumotte continued and resulted in the series of 2—3 February 1933 (12 sondes). Palmén (1935), Van Mieghem (1939C).

In this investigation 7 sondes were sent up at Uccle by telegraphic request of Palmén, as the state of the weather pointed towards interesting developments. In addition to this 5 sondes were sent up at Aas near Oslo. Thus for the first time a vertical section in a north—south direction was obtained, at the same time as an east—west section was obtained from a more northerly area than previously.

6. At Uccle a new series was sent up on 25 January 1935 (7 sondes). Van Mieghem (1937).

7. J. Bjerknes made plans to examine a strong cyclone in Northern Europe with the aid of simultaneous series of ascents at Aas, Riksgränsen in the far north of Sweden, and Lauttakylä in the south of Finland. At the same time an invitation was sent out by the Aerological Commission for all European observatories to collaborate. This invitation led to a large number of observations during the period 15—17 February 1935 — altogether 120 — of which 27 came from Aas, and 26 from Uccle. For the first time extensive synoptic-aerological material was thoroughly worked upon. J. Bjerknes and E. Palmén (1937), Van Mieghem (1939C).

8. A similar investigation from 17—19 October 1935 with serial ascents from Nesbyen in Norway and Filipstad in Sweden gave 21 and 11 soundings respectively. Synoptical material was also obtained from 34 ballons-sondes and a large number of soundings from aeroplanes. Nyberg and Palmén (1942).

Among later investigations the following may also be mentioned:

9. Series of 17—19 December 1936 (9 sondes at Uccle). Van Mieghem (1939 B).

10. In the series of 16—19 March 1937, 64 sondes were sent up at Uccle and 92 at others places. Unpublished.

11. During the period 13—18 December 1937 extensive synoptic-aerological material was obtained (approx. 200 soundings). J. Bjerknes, P. Mildner, E. Palmén and L. Weickmann (1939).

12. During 7—9 October 1938, 22 sondes at Uccle and a number of synoptical observations mainly from Central Europe. J. Van Mieghem and L. Dufour (1942).

From January 1st. 1933 charts showing pressure and wind at the levels of 3 000 and 6 000 feet were published in the English »Daily Weather Report». »Deutsche Seewarte» of Hamburg took up the suggestion of V. Bjerknes and J. W. Sandström (1910) to draw geopotential charts, and from the 1st. September 1934 a geopotential chart for 500 mb. has been published in »Tägliche Wetterbericht». Scherhag (1935 and 1936).

In the U.S.A. ballons-sondes were simultaneously sent up as early as in 1927 (30—31 December). From 10 stations 16 serviceable readings were obtained, all from places south of 40° N. The result of Emmons work (1935) upon this material was a type of synoptical height-chart, the first of its kind to show the distribution of air masses up to a height of 3 000 m.

In the U.S.A., Namias (1934 B), Wexler (1935) and Willett (1935) obtained sections during the years 1931—33. These sections were based on simultaneous observations from several stations. In contradistinction to the earlier European sections, they were true space-sections.

The synoptic-aerological investigations from the U.S.A. have all been made in fairly southerly regions, as a rule south of 45° N, and in Europe only a few synoptical observations have been made in upper layers of air north of 60° N. Attempts to obtain synoptical material from Riksgränsen at lat. 69° N met with failure, as the sondes were seldom found again in the sparsely populated districts of Lappland. Of 21 sondes sent up during the period 15—17 Febr. 1935 only one was found.

Through the construction of radio-sondes by Bureau and Moltchanoff, both in 1928, and later by Duckert and Väisälä and others[1], the readings were made independently of the physical surroundings of the ascent base. Thereby it was made possible to obtain aerological material from the North of Europe, and thus the synoptical part of the aerological investigation could be extended.

In April 1939 · · an international aerological month — soundings were made outside the then normal programme, especially in the North of Europe at places such as Reykja-

[1] See: Internationale Meteorologische Organisation (1937 and 1939).

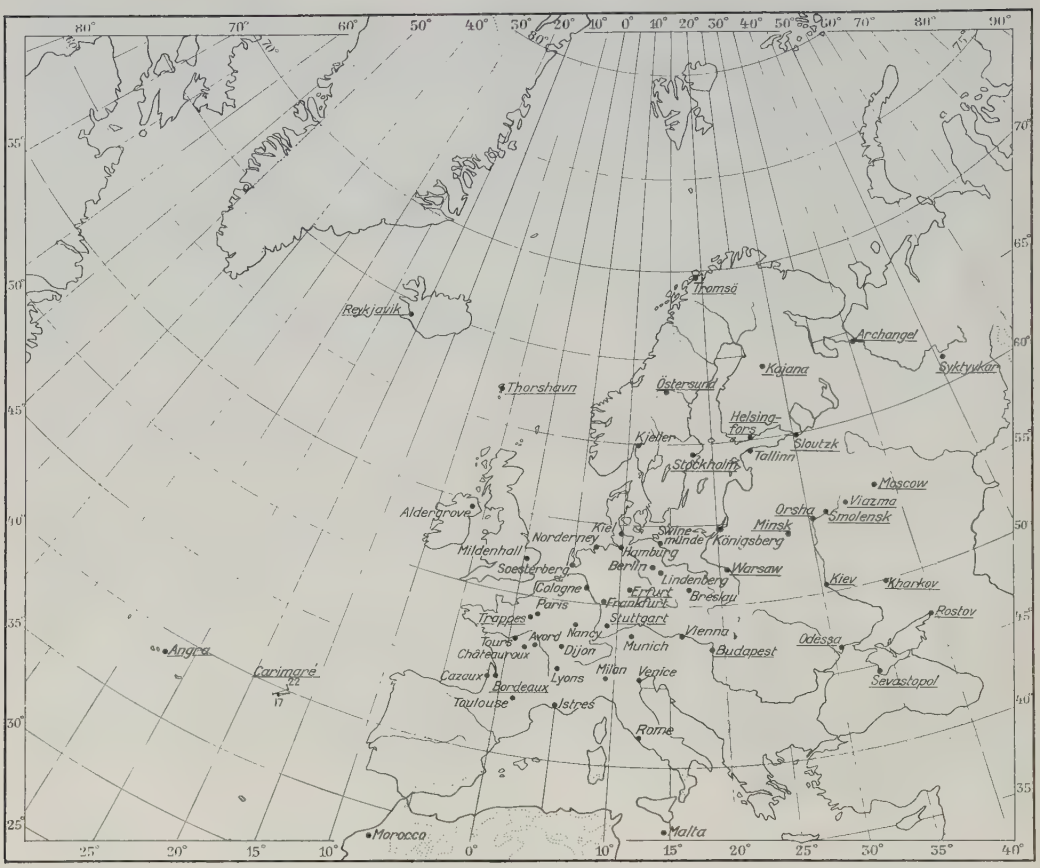



Fig. 1. Network of aerological stations. The balloon stations underlined.

vik, Thorshavn in the Faroe Islands, Tromsö, Kajana and Östersund, but also in western regions, for instance at Angra in the Azores and on the French ship Carimaré, at approx. 40° N, 17° W. During the aerological week 17—22 April the ascents were especially numerous. The material from this period is the most extensive available from any period in Europe and includes balloon soundings and aeroplane flights. The observations are so close together that space-sections can be drawn, and they cover such a large area that trajectories for 24 hours can be calculated even when the wind is strong. The positions of stations can be seen on the map (Fig. 1). The total number of the soundings reaches an average of 50 per day. In this investigation particular stress has been laid on the conditions of North-West and Central Europe.

## Material and Method.

### Aerological Material and Criticism Thereof.

On account of the War it has not been possible to obtain all the material collected during the period under survey. The author has himself carried out the soundings at Östersund, calculated the results, and checked the results of the ascents in Stockholm. These are included in the Swedish Meteorological-Hydrological Year Book, 1939, Part VI. Checked calculations of the soundings at Helsingfors and Kajana have been put at my disposal by the Finnish Meteorological Institute, Helsingfors. Results from Tromsö and Kjeller have been obtained from the Norwegian Meteorological Institute, Oslo. The results of ascents at Aldergrove, Mildenhall, Thorshavn, Soesterberg and Budapest have been obtained from the publications referred to in the bibliography (B II), and may be found under the respective headings. It has been necessary to take the remaining sounding results from Deutsche Seewartes Tägliche Wetterberichte. Considering the type of publication it is only natural that some errors have crept in there, but the given figures of geopotentials and temperatures at the standard pressures have been checked as soon as there has been an indication that an error might have occurred. The values of the characteristic points given in the bulletins have only been corrected in exceptional cases, as indicated in every special instance mentioned below.

The material is not homogeneous. The ascents at Thorshavn, Tromsö, Östersund, Stockholm, Kajana and Helsingfors have been carried out with Väisälä radio-sondes, the Russian ascents probably with Moltchanoff's apparatus, the French, Polish and Portuguese ones with Bureau's radio-sondes, the German radio-soundings, including those of Reykjavik, with Lang's sondes or the so-called Marin sonde. In addition there are a large number of aeroplane flights, of which the German ones are most valuable on account of their number and their descriptions of hydrometeors.

There is no general systematic comparison between these various types of instruments. It is true that comparisons between some of the instruments have been made, but as a rule the results of the examinations are not known. The Väisälä sonde described by Väisälä (1937) has been examined regarding lag error by Nyberg (1940), who found that at the normal rate of climb (5—6 m./sec.) it does not amount to more than 0.5°. The radiation error has been carefully examined by Väisälä (1941). Taking into consideration the low altitude of the sun during the morning hours of April in Northern Europe, the radiation error is insignificant, even in the stratosphere, being only 1—2° even at the 100 mb. level. A correction for the lag error or the radiation error has not been made, as there are good reasons to suppose that other instruments in use show similar or probably larger errors; thus a correction would reduce the comparability.

The aeroplane-meteorographs show temperature readings which are too high, partly on account of lag [Frankenberger (1935)], and partly because of the high speed at which the aeroplanes travel. According to Findeisen (1938 B), the error which arises on account of the speed is partly the result of the adiabatic heating in those parts of the instrument

which are normal to the direction of flight, and partly due to the friction in those sections which are parallel with the direction of flight. In both cases the error is approximately equal and proportional to the square of the aeroplane's velocity. In clouds the adiabatic heating is slightly less than in cloudless space. According to reports from the meeting of the Aerological Commission in Berlin in 1939, the German aeroplane soundings have been corrected for these errors which had been empirically determined by comparison with solid thermometers mounted on towers.

Reports from the Norwegian Meteorological Institute indicate that the data from Kjeller have not been adjusted for such errors, and it is obvious from the charts that the given values are too high. For the soundings Tiger Moth aeroplanes have been used. Their horizontal speed whilst climbing amounts to about 100 km. per hour and the rate of climb to about 2.5 m. per sec.

The lag error in the thermometer of the aeroplane meteorograph is in direct proportion to the rate of climb (Nyberg 1942). The rate of climb diminishes with the height, especially near the maximum height. According to measurements made by van der Maas and Wynia, quoted by Keil (1940), the speed error increases with height. In Table I we show the lag error in an aeroplane meteorograph with a horizontal speed of 120 km. per hour and next to it the speed error at a horizontal speed of 100 km. per hour, according to van der Maas and Wynia.

*Table I.*

| Height | Rate of Climb m. per sec. | Lag error | Speed error | Total error |
|---|---|---|---|---|
| near the ground ..... | 4.5 | 2.0° | 0.39° | 2.4° |
| 3 km. ..... | 2.9 | 1.7° | 0.52° | 2.3° |
| 5 km. ..... | 0.6 | 0.4° | 0,66° | 1.1° |

With the rate of climb of approx. 2.5 m. per sec. the lag error near the ground is 1.2° and the total error 1.6°; at a height of 3 km. the total error is slightly more and at 5 km. slightly less.

It is hard to reach an accurate determination of the error, as the type of aeroplane used and the way in which the meteorograph is mounted influence the results. The figures from Kjeller have not been corrected at all, but in drawing the isotherms the error has been assumed to be approx. 1.5°. This value concurs with those of Stockholm and Thorshavn if an average is calculated for all the soundings made during the month. In Table II is shown the geopotential which has been calculated from the given values, and from values corrected by 1.5°. The soundings from Soesterberg seem to have been corrected for the above mentioned error.

In examining the English soundings it was observed that in fresh polar air with showers such as prevailed at Mildenhall on the 22nd. April at 0600 hours GMT they showed indifferent stratification, as is usual in such cases. From this observation and by comparison between the relative topographies of simultaneous investigations at Aldergrove, Hamburg and Königsberg, and Mildenhall, Cologne and Breslau, places situated in

groups at the same latitudes (see Tab. II), the conclusion was drawn that possible systematic errors were small. Subsequently information has been obtained from the Meteorological Office, London, that the observations have certain minor systematic errors, which are shown in Table III.

*Table II.*

a)

| | Thorshavn | Kjeller | Kjeller corr. | Stockholm |
|---|---|---|---|---|
| $\Delta \sigma_1$ | 2 745 | 2 789 | 2 774 | 2 767 |
| $\Delta \Phi_2$ | 2 446 | 2 465 | 2 450 | 2 451 |

Calculated for the days 3, 6 11, 12, 14, 20—22 and 28 April.

b)

| | Aldergrove | Aldergrove corr. | Hamburg | Königsberg | Warsaw |
|---|---|---|---|---|---|
| $\Delta \Phi_1$ | 2 794 | 2 779 | 2 802 | 2 787 | 2 799 |
| $\Delta \Phi_2$ | 2 501 | 2 486 | 2 492 | 2 476 | 2 502 |

Calculated for the days 2, 3 6—8, 12—14 16—25, 27, 29 30 April.

c)

| | Mildenhall | Mildenhall corr. | Cologne | Breslau |
|---|---|---|---|---|
| $\Delta \Phi_1$ | 2 806 | 2 791 | 2 810 | 2 820 |
| $\Delta \Phi_2$ | 2 489 | 2 474 | 2 491 | 2 502 |

Calculated for the days 1, 3 —6, 11—15, 17—22, 24—29 April.

d)

| | Thorshavn | Reykjavik |
|---|---|---|
| $\Delta \Phi_1$ | 2 755 | 2 760 |
| $\Delta \Phi_2$ | 2 454 | 2 453 |
| $\Delta \Phi_3$ | 3 424 | 3 451 |
| $\Delta \Phi_4$ | 2 602 | 2 567 |

$\Delta \Phi_1$ and $\Delta \Phi_2$ are calculated for the days 2—30 April. $\Delta \Phi_3$ and $\Delta \Phi_4$ are calculated for the days 2, 3, 5—9, 11, 13, 16, 18—24, 26, 27, 30 April.

Comparison between the geopotential differences 700 -1 000 mb. $\Delta \Phi_1$, 500—700 mb. $\Delta \Phi_2$, 300—500 mb. $\Delta \Phi_3$ and 200—300 mb. $\Delta \Phi_4$. The figures given are mean values calculated from figures obtained from the relevant bulletins on the days annotated above on the right-hand side. In the column »Kjeller corr.» the temperature values have been decreased by 1.5°, while in the columns »Aldergrove corr.» and »Mildenhall corr.», they have been decreased in accordance with Table III.

*Table III.*

*Errors in the English Soundings in April 1939.*

| | | |
|---|---|---|
| 1 000—750 mb | 1.5°F | 0.8°C |
| 650—550 mb | 2.0°F | 1.1°C |
| 500 450 mb | 2.5 F | 1.4°C |
| 400 mb | 3.0 F | 1.7°C |

These figures were received so late, that it has been impossible to correct the values used in drawing geopotential charts and vertical sections. However, the errors are of small importance, and have been disregarded. Regarding the figures of Table II it is even doubtful whether this correction really improves the concurrence between the English and German temperatures. However, in studying air movements from day to day the wet-bulb potential temperatures have been corrected according to the above values, for reasons which will appear later (p. 89).

In the construction of certain height-charts use has been made of temperature observations made from passenger aeroplanes belonging to the Swedish Air Lines. Comparative measurements were made by the author in the Spring of 1939 at Bromma aerodrome with an Assmann psychrometer and the aeroplane's thermometers at the moment when the plane left the ground. It was found that the aeroplane thermometers showed values 2—3° higher than the actual temperature of the air.

The German radio-sonde stations Erfurt, Stuttgart and Cologne have all given considerably higher temperature readings than the aeroplane soundings, whereas the temperatures from Hamburg appear to be more reliable. Compare for instance aeroplane observations from Hamburg at 0400 hours GMT on April 23rd. and observations with a radio-sonde at 0600 hours GMT at the same place. (Deutsche Seewartes Bulletin and Fig. 42). The correlation is satisfactory up to the maximum height of the aeroplane.

The soundings at Reykjavik carried out by Germans have been compared with the soundings at Thorshavn for the whole month, and the results can be seen in Table II.

Considering the more northerly position of Reykjavik, a lower temperature might be expected in the troposphere, and a somewhat higher one in the stratosphere, compared with Thorshavn. Thus it would seem that the figure for the average temperature is too high in the troposphere for Reykjavik. It has not been determined whether this is due to a systematic error or to occasional values which are too high. Further discussion of the table will follow below.

In each separate sounding errors of a more or less fortuitous character may arise. In checking certain soundings which were obviously incorrect, the assumption has been made that a constant error in pressure or temperature was present at all the characteristic points of these soundings. Attempts to improve the soundings on the basis of this assumption have been treated in detail by Nyberg and Palmén (1942), making use of serial ascents. A similar method can be used if comparatively good synoptical height-charts are available. In this case it must be assumed that at each equipotential surface the isogeopotential lines run with the same degree of continuity as the isobars at ground level. The geopotential difference between two points with the pressures $p_1$ and $p_2$ can be calculated with the barometric height formula $\Phi_{2-1} = RT \ln \frac{p_1}{p_2}$, which has approximate validity if $T$ is given as the mean temperature of the layer $p_1$—$p_2$. In practice the differences are obtained with the aid of an adiabatic paper or of tables (e. g. from V. Bjerknes and J. W. Sandström 1910). The geopotential error $\Delta\Phi$ caused by the temperature error $\Delta T$ can be written $\Delta\Phi = \Delta TR\,(\ln p_1 - \ln p_2)$ and thus only varies with $\Delta T$, $p_1$ and $p_2$.

Table IV shows the geopotential error that arises through a temperature error of 1° and a pressure error of — 10 mb. The geopotential error caused by a constant temperature error is independent of the course of the temperature curve, whereas the geopotential error arising through a constant pressure error is dependent on the temperature as well as on the course of the temperature-height curve. The values in Table IV are therefore only examples calculated for a curve with the ground values at sea level $p$ = 1 000 mb., $T$ = 10° and with the temperature gradient equal to the saturated adiabatic up to a level of 300 mb., and thereafter = 0.

*Table IV.*

| Pressure in mb. | 1 000 | 900 | 800 | 700 | 600 | 500 | 400 | 300 | 200 | 100 |
|---|---|---|---|---|---|---|---|---|---|---|
| a..... | 0 | 3 | 6 | 10 | 15 | 20 | 26 | 35 | 46 | 65 |
| b..... | 0 | 2 | 5 | 8 | 11 | 17 | 25 | 40 | 43 | 43 |
| c = a — b ..... | 0 | 1 | 1 | 2 | 4 | 3 | 1 | — 5 | 3 | 22 |

The geopotential error in gm. in standard pressure levels for a) a temperature error of one degree. b) a pressure error of — 10 mb.

The table is calculated from a sounding starting from ground-level at a temperature of 10°. The vertical lapse rate up to 300 mb. corresponds to the moist-adiabatic. At higher levels the conditions are isothermal.

In the troposphere the geopotential error caused by a pressure error of —10 mb. is of practically the same degree as that which is caused by a temperature error of 1°, but in the stratosphere the pressure error does not increase if isothermic conditions prevail. If the soundings reach the stratosphere and there is a sufficiently close net of observations, there is a possibility of determining not only the existence of an error but also whether it is a pressure error or a temperature error.

As has been pointed out by Nyberg and Palmén (1942) the method of evaluation may cause geopotential errors of such dimensions that they cannot be disregarded; for example in cases where the distance between the two characteristic points is great. In the material used for this investigation, however, the distance between the given characteristic points was never so great that the error caused needed to be taken into consideration, as according to calculations it never exceeded 10 gm. Let us take as an example an ascent at Warsaw on 24 April at 0700 hours GMT, where the characteristic points are relatively sparse. We assume that in a right-angled system of coordinates with the axes $T$ and log $p$ the temperature curve is a straight line between the given points 586 and 365 mb. Then the geopotential difference amounts to 3 355 gm. If the geopotential difference is calculated, assuming that the temperature curve is a straight line in the right-angled system of coordinates $T$—$p$, the value 3 346 gm. is obtained. The difference of 9 gm. is of minor importance considering the accuracy of the figures for temperature and pressure and the errors in the geopotential thereby caused.

We return to the comparison of figures obtained at Reykjavik and Thorshavn (Tab. II). Whereas one would expect the tropospherical temperature at Reykjavik to be lower than that at Thorshavn considering the more northerly position of the former place, there is actually no visible difference. We cannot definitely claim that Reykjavik must be colder, but it is highly probable, and a possible error should have the average value of 2° or 20 mb. in view of the normal horizontal temperature gradient along a meridian. If we assume a systematic temperature error, the same error should occur in the stratosphere, which on account of the geographical position should be warmer at Reykjavik than at Thorshavn. This is, however, not the case with the values found. Nor can the temperature differences obtained be explained by assuming only a systematic pressure error, for in such a case the geopotential difference Reykjavik—Thorshavn would remain constant with the height, or only increase to a very small degree. By combining the errors of pressure and temperature the geopotential difference at various levels could be explained, but in that case errors as large as $p = 40$ mb. and $T = -4°$ would have to be assumed, and it is hardly possible that such large systematic errors occur. It is, of course, not improbable that errors occur also in the observations from Thorshavn, but as these have been carried out with the same instruments as all other soundings in Scandinavia and Finland, it is most reasonable to assume that the error is to be found only at Reykjavik. Thus by a correction this latter could be brought to correspond with the other soundings. As can be seen from the above it is hardly conceivable that prevailing systematic errors have caused the existing geopotential differences. It is therefore to be assumed that some of the separate soundings have involved errors of temperature or pressure or both, for which reason the mean temperature value has been increased in the troposphere and lowered in the stratosphere. On account of Reykjavik's position on the outskirts of the area observed, it has, as a rule, not been possible to make corrections.

## Construction of Geopotential Charts.

In drawing height-charts (or more correctly, geopotential charts) the same method has been followed as that used by Deutsche Seewartes Weather Bureau, Hamburg, (see for instance Scherhag 1935 and 1936). First a map is drawn for 1 000 mb. based on pressure and temperature readings at ground level. Example: A station with the readings $T = 10°$ and $p = 1\,015.3$ mb. (reduced to sea level) situated 50 m. above sea level, has its 1 000 mb. level at a height of 125 gm., which can be calculated most readily with the aid of an adiabatic paper. In the relevant cases it is assumed that the temperature rises by 0.5° per 100 m. descent. After this a relative topographical map is drawn for 700 mb. on which the geopotential differences between 700—1 000 mb. are marked for the aerological sounding stations. The charts are completed under the assumption that a saturated adiabatic gradient prevails within the area when a strong current of air causes widespread showers, i.e. in labile cold air. This assumption is verified by soundings in shower areas, and this method is in general use. For the intermediate

areas, a temperature gradient has been assumed, which is approximately 2° per 1 000 m. lower than the temperature gradient of the saturated adiabatic. In addition we have tried to calculate with the trajectories of the previous 24 hours and have thus obtained certain data concerning the value of the relative topography.

Interpolations have been made between the figures thus obtained. In drawing relative topographies in areas in which fronts or frontal zones exist, it must be observed that isolines for the relative topography become more dense than otherwise over the whole area of the front — in this case from the intersection of the 1 000 mb. level with the front to the frontal intersection of the 700 mb. level. This question is treated more extensively below in connection with the drawing of isohyps for absolute topographies. When the relative topographical chart has been completed, the absolute topography is obtained by choosing suitable points and then adding the values of the absolute topography of the 1 000 mb. level and the relative topography of the 700 mb. level. On the 700 mb. chart values for the absolute topography of all aerological stations that have reached this level are plotted. In addition figures obtained by extrapolation have been plotted, if the highest point is less than 50 mb. from 700 mb., and these stations are marked on the map by an apostrophe after the temperature figures. The same method is also applicable to the 500, 300 and 200 mb. charts. The observations which do not come so near the pressure levels have also been used in drawing the relative topographical charts, for an extrapolation from, for instance, 800 mb. to 700 mb., is obviously more reliable than one from 1 000 to 700 mb. From the absolute topography for 700 mb. we have found the absolute topography for 500 mb. by drawing a relative topographical chart which shows the geopotential difference between 500 and 700 mb. It has been obtained in a similar manner to the previous relative topographical chart. The assumption has been made that the indifferent stratification in northerly precipitation areas with snowfall has ceased at the 700 mb. level, and above that a faint moist stability has prevailed. The absolute topography for 500 mb. has been obtained by adding the absolute topography for 700 mb. to the relative topography for 50c—700 mb. In the same way relative topographical charts for 300—500 mb. and 20c—300 mb. have been drawn and from them the absolute topographies for 300 and 200 mb. have been obtained.

In drawing synoptical height-charts all soundings have been plotted independently of when they were made. Russian soundings from 0300 or 0400 hours GMT, German soundings between 0500 GMT and 0800 GMT and other soundings at times between these are plotted on the same chart. As a rule the errors which arise on account of this are insignificant, and all soundings can be regarded as made at 0700 hours GMT as in the case of the observations for ground charts. In certain cases, as for instance near fronts or when changes of temperature and pressure are rapid, the differences of time which occur must be taken into consideration. This has been done in drawing the isotherms and isogeopotential lines, but not in plotting the given station values on the charts.

On the height-charts unbroken lines representing isogeopotential lines have been drawn for every 50 gm., and dotted lines representing isotherms for intervals of 2.5°. In a

definition of fronts and frontal zones, Bergeron (1928) has given the order of magnitude of the breadth of the front as $10^4$ m., and the breadth of a frontal zone as $10^5$ m., in which case the differences of temperature between the outer limits of the front and frontal zones would amount to 1°—10°. This definition is valid for ground conditions. In higher layers of air the fronts are generally wider than at ground level and here the order of magnitude can be taken as $10^5$ m. for a front and $10^6$ m. for a frontal zone. The vertical thickness of the front can be put at $5 \cdot 10^2$—$10^3$ m,, and the vertical extension of the frontal zone at $10^3$—$10^4$ m.

The fronts have been drawn in different manners in order to indicate their varying degrees of sharpness. Such fronts as are well defined by soundings have been drawn with continuous double lines, which show their horizontal extension. Less clear fronts, which are nevertheless in a certain degree evidenced by height-observations, are represented by double broken lines. Fronts that have been identified with the aid of ground charts, but whose existence cannot be established with certainty by height-observations, have been drawn as single lines, continuous or broken, according to the degree of certainty of their presence. Frontal zones have not been specially indicated. Their positions can be seen from the density of the isotherms. In the application of such a classification of fronts a certain arbitrariness cannot be avoided.

A thick continuous line has been drawn on the 300 mb. charts which indicates the intersection of the 300 mb. level with the tropopause surface. To the north of this line the 300 mb. level lies in the stratosphere, to the south in the troposphere. In cases where the tropopause is multiple a mean value has been taken, which introduces a certain arbitrariness.

Note should be taken regarding the drawing of isogeopotentials in frontal regions. This question has been dealt with by Bjerknes and Palmén (1938) and later on by Palmén in a still unpublished work, and it will be treated in the present investigation. Let us assume a front moving at right angles to the current which, to start with, for the sake of simplicity, is assumed to be rectilinear. At the points from A to G along the horizontal line A—G which is parallel with the current and which has the pressure of 1 000 mb. soundings have been carried out which give the vertical section in Fig. 2. Everywhere outside the front the temperature falls by 5° per 1 000 m. vertically and 1° per 100 km. horizontally parallel with the current. At right angles to the current we have a constant temperature gradient. In the calculations made below we assume this gradient to be small. In the front vertical isothermal conditions prevail. The slope of the front is 1:100 and its depth 1 gkm. We calculate the relative topography for a number of points situated on the 700 mb. level vertically over A to G, and the corresponding points vertically over the isobars 980 and 1 020 mb. etc. Then we find (see Fig. 3 a) that the relative isohyps (or more correctly, isogeopotentials) are rectilinear in advance of the perpendicular line over B, curved like an anticyclone (Acy) vertically over B and C, once again rectilinear over the front region C—D and cyclone-curved (Cy) at the front zone, where this is intersected by the 700 mb. level (D—E) finally to become rectilinear as before.

Contrary to what has been assumed the current at ground level is not rectilinear at the front. The barograph curve usually shows a more or less distinct discontinuity at the front, and the isohyps on the height-chart for absolute topography should therefore have an aspect divergent from Fig. 3 a. The above calculations have, however, a certain

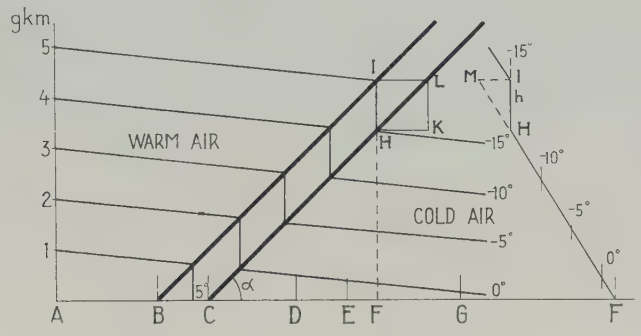



Fig. 2. Schematical cross-section and temperature-height diagram through a front-surface.

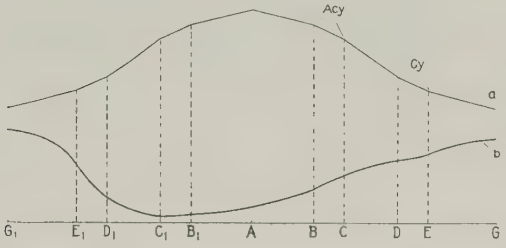



Fig. 3. The isogeopotential at 700 mb. Right: over a warm-front. Left: over a cold-front.
a) relative geopotential.
b) absolute geopotential.

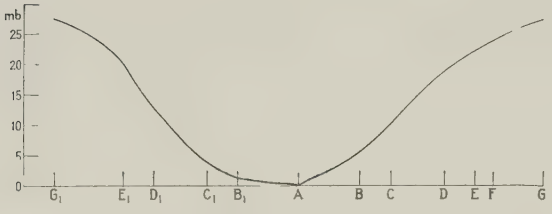



Fig. 4. Variations in pressure at ground level at the passage of a warm-front and a cold front. Schematical.

general application, if in each case one calculates the difference between the geopotential in the figure and the geopotential from the barograph curves or from the ground charts. This difference is added to Fig. 3 a. We have used this method and calculated the appearance of the height-chart both for a warm-front and a cold-front (see Fig. 3 b, where the warm-front's course is shown on the right and the cold-front's on the left).

The barograph curve is of the usual type for these fronts, and its appearance is shown in Fig. 4. The result for the 700 mb. level in the chosen case is, in the warm-front, a slight anticyclonic curvature of isogeopotentials with a stronger anticyclonic curvature before and after the front, as well as perpendicularly over the ground warm-front. The curvature is very slightly cyclonic vertically over the cold-front at ground level. At the cold-front we have a strong cyclonic curvature, preceded by a weaker cyclonic curvature and followed by an anticyclonic curvature. In cases where the aerological material is limited and the calculated points on the absolute topographical chart are few, it is of special importance to observe the fronts registered in the soundings and to take into consideration their effect on the course of the isohyps according to the above method. If this is not done it is highly probable that the isohyps are given a more even course and that the front in the height-chart does not become visible, despite the fact that it actually exists. It is obvious that this general anticyclonic curvature over the warm-front surface or the cyclonic curvature over the cold-front surface is likely to obscure the fronts in the free atmosphere. In a rectilinear progression of the isohyps these would appear, even if the net of observations were very sparse. At ground level the discontinuities in the front are purposely accentuated in order to point out the essential characteristics. In doing this, the influence of friction on the wind is taken into consideration, as also are discontinuities in precipitation, clouds etc. From the material examined, it is clear that from a thermal point of view the fronts are not always clearer at the ground than higher up; on the contrary, at least some warm-fronts are obscure at the earth's surface, on account of a persisting cold air skin. Compare the warm-front of 19th. April at 700 mb. and at the ground. Scherhag's question (1937) »Warum gibt es in der Höhe keine Fronten?» may apparently be answered with the facts that the curvature of the isohyps often becomes less pronounced at high levels, and that the net of observations is so sparse that the course of the isohyps cannot be determined. This latter is the main reason.

In drawing the height-charts, the question also arises how many isotherms should be drawn in the front. We start from the same conditions as in drawing the vertical sections (Fig. 2) and assume that the fall of temperature A—G is 1° per hundred km. outside the front. As J. Bjerknes and E. Palmén (1938) have indicated, the decrease of temperature in the front is obtained through extrapolation of the section of the temperature-height curve FH that lies beneath the front and extends to the upper level M of the front. This, however, is not the complete temperature fall. Let us study Fig. 2.

A front, the slope of which is $\alpha$, has the vertical thickness $h$. The vertical lapse rate in cold air is $a$. The lapse rate in the front is $b$ (in the figure $= 0$). The horizontal gradient along $AD$ outside the front is $c$.

The temperature at H $= T_0$

» » » I $= T_0 + hb$

» » » K $= T_0 + ch \cot \alpha$

» » » L $= T_0 + ch \cot \alpha + ha$

» » » M $= T_0 + ha$

whence the temperature difference I — L = (I — M) — $ch \cot \alpha$

The temperature difference between the upper front level I and the point M obtained by extrapolation only shows part of the horizontal temperature fall in the front. To this is to be added the temperature change $-ch \cot \alpha$, which would have been situated within the area occupied by the front, even if no front had existed. This change of temperature is calculated from the horizontal extension of the front and the horizontal temperature gradient outside the front. The latter quantity must not be disregarded, as when drawing a weak front with strong baroclinicity in the surrounding air, this might even lead to a greater concentration of isotherms outside the front than inside it. In the above mentioned example, 5° is obtained from extrapolation of the temperature-height curve and approximately 1° from the horizontal gradient. From this the conclusion is drawn that six full degree isotherms are included in the front.

In the drawing of the front patterns, the greatest possible consideration has been given to the results quoted, however, it has not been possible consistently to make use of the above results, as the distinctness of the fronts within small areas may vary considerably and the charts would lose their lucidity if the above principles were dogmatically adhered to.

## Drawing of Vertical Sections.

The height-charts are supplemented by vertical sections. In drawing these sections a logical agreement between the sections and the charts has been aimed at, but it would seem impossible to avoid small inadvertencies in certain cases. It is, however, probable that this does not influence the following discussion or the results presented.

Sections have been drawn showing distribution of temperature. The use of temperature in air mass analysis, as is well known, is limited, as it is changed by the dry adiabatic processes as well as by the saturated adiabatic processes and the evaporation of water into the air.

The relative humidity which, as in the case of temperature, is obtained direct from observations, is of great immediate significance in judging the physical condition of the air, but like the temperature it has a limited use in air mass analysis. Many attempts have been made to find a factor which in itself expresses the temperature and humidity of the air and is completely independent of all adiabatic changes. Here a brief account will be given of the more successful of these experiments. Unless otherwise stated the figures and definitions mentioned below are in agreement with Bleeker (1939).

von Bezold (1905) introduced the concept *(isobaric-)equivalent temperature* $T_i''$, which is the temperature that air would assume if all vapour was condensed at constant pressure, and if the heat of condensation was used to increase the temperature of the air.

The *dry-potential isobaric-equivalent temperature* $\Theta_i''$ is obtained from an adiabatic paper as an intersection between the dry adiabatic through $T_i''$ and 1 000 mb. This factor, which has also been called «äquivalentpotentielle Temperatur», has been generally used in air mass analyses by, among others, Schinze (1932 and 1938). The potential isobaric-equivalent temperature is, however, only conservative regarding the evaporation

of rain which has fallen through the air, but not in adiabatic processes, and it is therefore unsuitable for air mass analyses.

Stüwe (1927) introduced the *adiabatic equivalent temperature* $T_a''$. This is the temperature attained by a particle which is moved upwards along the dry adiabatic to its condensation level, then along the saturated adiabatic until all the water has been removed, and finally along a dry adiabatic to its original pressure.

*The dry potential adiabatic equivalent temperature* $\Theta_a''$ is obtained by intersection of the dry adiabatic through $T_a''$ and the 1 000 mb. isobar on an adiabatic paper. $\Theta_a''$ was called by Stüwe »pseudopotential temperature» and by Rossby (1932) »equivalent potential temperature». Petterssen (1939) uses the expression »potential equivalent temperature».

*The adiabatic wet-bulb temperature* $T_a'$ was defined by Normand (1921) and Brunt (1934). $T_a'$ is the temperature which a particle of air attains if it is moved along a dry adiabatic to the level of condensation and then along a condensation adiabatic until it reaches its original pressure.

*The adiabatic wet-bulb potential temperature* $\Theta_a'$ (Brunt 1939) is the temperature which is obtained at the intersection of the condensation adiabatic through $T_a'$ and 1 000 mb. on the adiabatic paper. Petterssen calls $\Theta_a'$ the potential pseudo-wet-bulb temperature. In synoptic-aerological works $\Theta_a'$ is generally called the *wet-bulb potential temperature*.

In air mass analyses a factor should be used which is conservative in all adiabatic and non-adiabatic changes occuring in nature. None of the potential temperatures mentioned here and none of those which are to be found in the literature fulfil these requirements (Möller, 1939). According to Petterssen (1939) and Bleeker (1939 and 1940) the potential adiabatic equivalent temperature and the wet-bulb potential temperature are decidedly superior to other factors, as they are conservative in dry adiabatic processes as well as in saturated adiabatic processes, and can only be changed a few tenths of a degree through the evaporation of water. In relation to each other they are practically equivalent. Primarily because the wet-bulb potential temperature is easier to calculate, it has been used in this investigation. In synoptical work it was presumably first used by Hewson (1936).[1] The errors in the humidity figures, which influence the wet-bulb potential temperature, would affect all other temperature-humidity factors and are inevitable. Fortunately the hygrometers are fairly reliable at high temperatures, when the influence of relative humidity on the wet-bulb potential temperature is considerable, while the limited precision of humidity readings at low temperatures is followed by a reduced influence of the relative humidity on the wet-bulb potential temperature. One can estimate the error which the lack of precision in humidity determination causes in the wet-bulb potential temperature as, as a rule, less than 1°. In individual cases a correction of the relative humidity can be made. This applies, for instance, if the balloon is observed to vanish in thick clouds without the hygrometer having shown saturation point. Because of the lag in the instrument the hygrometer never registers the maximum

[1] In the course of this work Väisälä (1943) has indicated a simple method of calculating the entropy of the air, a factor equivalent to the wet-bulb potential temperature. This method, however, has never yet been used in synoptical investigations.

value in thin clouds at low temperatures (Nyberg 1940). If the cloud is a water cloud one assumes the humidity to be 100 %. If it is an ice cloud the humidity is calculated to correspond to saturation over ice. If it cannot be established whether ice or water cloud occurs, the humidity value should still not be assumed to be lower than the equivalent saturation over ice at the temperature in question.

In calculating the wet-bulb potential temperature Refsdal's adiabatic paper has been used (Refsdal 1937). In his paper sublimation adiabatics at temperatures below 0° are indicated. An air mass which rises upwards and which contains so much moisture that condensation takes place at a temperature above 0°, can completely or partly have given off the water as rain when the zero degree level is reached. To what extent this has occurred cannot be determined with the aid of soundings. With further elevation above the zero degree level the water in the form of drops must either freeze, after which the temperature follows a sublimation adiabatic, or not freeze, in which case the temperature follows a condensation adiabatic for supercooled water until freezing takes place at a lower temperature. The released quantity of heat then reduces the fall in temperature. At yet a higher level the temperature follows a sublimation adiabatic. In the former case the amount of water in drops must determine the increase in the wet-bulb potential temperature.

Let us assume a ground temperature of max. 20° in the investigation district and a relative humidity of 80 %. If all the water condensed in an ascent to the zero degree level, approximately 6 g. per kg. air, were to stay in the air until freezing occurred at 0°, a quantity of heat would be released, 80 × 6 gcal. per kg. air, sufficient to raise the temperature of the air by 2.0°. In that case the wet-bulb potential temperature would be 1.0° *higher* than if all the condensed water had been precipitated. The latter is assumed in calculating from Refsdal's adiabatic paper. In the other case the air mass follows a condensation-adiabatic to start with, and is thus cooled more rapidly than the sublimation-adiabatic indicates. Its future properties depend on whether the condensed water is precipitated or not. If a precipitation occurs, the wet-bulb potential temperature becomes lower than if the sublimation adiabatic had been followed. If the same air as in the previous example were elevated and supercooled to a temperature of — 20°, the temperature would be approx. 4.5° lower than after elevation and freezing, but only about 1.5° lower than the value calculated from Refsdal's adiabatic paper, and the wet-bulb potential temperature would only be approximately 0.8° *lower*. From this we see that variations amounting to approx. 1° of the wet-bulb potential temperature in relation to that calculated from Refsdal's adiabatic paper are possible. As we have no possibilities of judging the physical conditions of water in the atmosphere and cannot calculate the amount of water given off, we cannot make a correction for possible errors, but they have been taken into consideration in the following analysis.

When drawing a cross-section the stations which are to be shown in the section are plotted on the horizontal axis. The vertical axis gives the geopotential in gkm. The section is generally made at approximately right angles to the fronts. As some stations are situated outside of the line of intersection, their projection is made on the line of

intersection, and from the points thus obtained perpendicular lines are drawn on which the temperatures of the soundings are plotted. With this method certain errors may creep in. In the first place the distance from the intersecting line generally means that the temperature differs somewhat on the measured line from that on the actual line of intersection. If the distance is small, this difference can be disregarded. Nevertheless, as will be shown below, the error may become significant if the distance is great. In this case it is necessary to correct for it with the aid of synoptical height-charts, or at least in the analysis to take into consideration the changes involved by spreading from the vertical plane.

In drawing the section there is another source of error. The soundings have not been made at exactly the same times. This can be partly compensated by displacing the soundings which refer to a time other than that for which the section is intended to be valid. They should be shifted in such a direction that their position in relation to the disturbance becomes the same as it was at the time when the observation was made. This method has been used when drawing cross-sections based on serial ascents from a single station (e. g. J. Bjerknes, 1932). However, this method involves great risks.

For the individual change $\frac{d\Theta'}{dt}$ of the wet-bulb potential temperature $\Theta'$ in a mobile air mass the following equation is valid, if heating or cooling by radiation is neglected:

$$\frac{d\Theta'}{dt} = \frac{\partial\Theta'}{\partial t} + v_x \frac{\partial\Theta'}{\partial x} + v_y \frac{\partial\Theta'}{\partial y} + v_z \frac{\partial\Theta'}{\partial z}$$

Assuming only adiabatic changes of state we can also put $\frac{d\Theta'}{dt} = 0$. The $x$ axis is laid in the plane of the cross-section and the system of coordinates is moved along the $x$ axis with the velocity $v_x$.

$$\text{Then } v_x \frac{\partial\Theta'}{\partial x} = 0.$$

However, the temperature change $\frac{\partial\Theta'}{\partial t}$ at a fixed point in the system of coordinates, i. e. in the section drawn, can be considerably influenced by $v_y \frac{\partial\Theta'}{\partial y}$ and $v_z \frac{\partial\Theta'}{\partial z}$.

In sections drawn on the basis of serial ascents without consideration of the effect $v_y \frac{\partial\Theta'}{\partial y}$, which is formed by the component of the wind at right angles to the front's direction of movement, the picture obtained may be a very distorted one. It is usual that excessively large contrasts of temperature are obtained, as the soundings in the warm air refer to the warm period of the cyclone when $v_y \frac{\partial\Theta'}{\partial y} < 0$, whereas the latest soundings pass through the cold air which has gradually descended in the rear of the cyclone. Then $v_y \frac{\partial\Theta'}{\partial y} > 0$ (in a west wind cyclone). In sections based mainly on synoptical material, i. e. space-sections, the differences occurring in time must also be observed, and

if possible be corrected with the aid of height-charts. We illustrate the above reasoning with an example.

Let us imagine a section drawn on the basis of observations at, for instance, Aberdeen on April 21st. at 0700 hours GMT and 1800 hours GMT and on April 22nd. at 0700 hours GMT. At 700 mb. the temperatures at these three points would be — 7°, — 9° and — 17°. A section drawn on the basis of synoptical observations at 1800 hours GMT on the 21st., carried out at the same parts of the disturbance, would give different results. After interpolation between the charts at 0700 hours GMT on the 21st. and 22nd., the values — 10°, — 9° and — 14° are obtained.

In analysis J. Bjerknes and E. Palmén (1937), Van Mieghem and Dufour (1942) and others have observed that the potential adiabatic-equivalent temperature and the

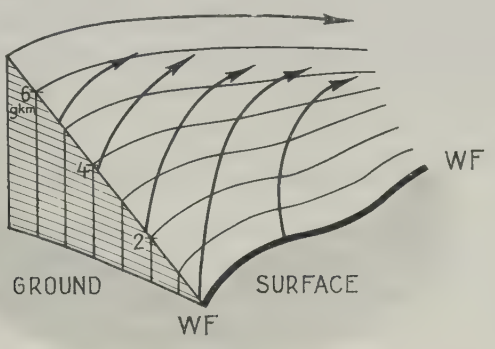



Fig. 5. Streamlines for the motion of the warm air in relation to the mobile warm-front surface.

wet-bulb potential temperature are constant along the front surface of a section, and this has been regarded as evidence of, or a consequence of, the upward gliding motion along the front surface, so that the air mass is identical along the front. As the height-charts show, and as Bjerknes and Palmén (1937) have clearly shown, the upward gliding motion does not occur in the vertical plane, but the upward moving air mass has a varying component in space at right angles to this plane. As the speed and wind-direction differ at the various levels, those particles of air which, at a given moment, are situated at different heights along the intersection of a front surface with the vertical section, will have come from completely different places. If the gradient wind is calculated at different levels of the front surface, a three-dimensional current of the type shown in Fig. 5 is obtained. Here the component of the direction at right angles to the front decreases with the height, so that at an average height of 5 km. the component corresponds to the velocity of the front, and this becomes the highest level which has upward gliding clouds. Along this line of current, which cannot be represented in an ordinary section, the wet-bulb potential temperature is, under certain conditions, constant. If barotropy prevails in the warm air, it is also to a large extent true that the wet-bulb potential

temperature is constant up to a height of 5 km. in a cross-section. If we believe that there are reasons to expect correspondence of the values for the wet-bulb potential temperature in the front surface even in a baroclinic warm air mass, we must suppose that the air at high levels originally has come from the ground, and there had the same value as the air at ground level at the time of the section. However, it seems more probable that the air at high levels of the front, which has a more northerly course, but which in spite of this has the same wet-bulb potential temperature as the air at lower levels, has not glided up from the ground but only from a higher level, which earlier already had a high wet-bulb potential temperature in spite of its more northerly origin.

Thus, if the wet-bulb potential temperatures are the same along the front, it must be regarded as a mere chance, and only with caution should this principle be used in drawing fronts. It is a phenomenon which can occur in one or two cases, but which has no general application. This is evident from the case in February 1935, in a comparison of Ås with Central Europe, described in the above quoted work by Bjerknes and Palmén.

## Calculation of Air Movements.

In studying the movement of air masses and fronts from day to day different methods can be used. The main stress can be laid on the position of the fronts, which are identified with the aid of discontinuities in the temperature-height curves, and the wet-bulb potential temperature. This method is especially suitable when the synoptic material is limited, and serial ascents form the main part of the material. If the synoptic material is more abundant one of the following methods may be used. Rossby et al. (1938) draws synoptic charts of the entropy, so called isentropic charts, according to a suggestion by Shaw (1930), and assumes that the current moves in and along the isentropic surfaces. Isolines for the specific humidity, plotted on the charts, aid in the following of air masses from day to day. The isentropic analysis is not suitable for use in cyclones where the specific humidity changes with condensation. We shall follow another procedure used by Shaw (1903) and by Shaw and Lempfert (1906) and draw trajectories with the aid of synoptical height-charts. The wind is calculated from the gradient wind equation

$$2\,\omega\, v \sin\varphi \pm \frac{v^2}{r} = -\frac{1}{\varrho}\cdot\frac{\partial p}{\partial n}$$

In calculating the wind at different levels, one of the advantages of geopotential charts becomes apparent. The same quantitative calculations of the wind can be used at all levels. Let us imagine a chart where the horizontal difference between two geopotential lines $\Phi_1$ and $\Phi_2$ (drawn for instance at every 50 gm.) is $n$ cm. The horizontal pressure difference $p_2 - p_1$ is then $-\varrho\,(\Phi_1 - \Phi_2)$ and $\frac{p_2 - p_1}{n} = -\frac{\varrho\,(\Phi_1 - \Phi_2)}{n}$, whence follows the gradient wind equation $2\,\omega\, v \sin\varphi \pm \frac{v^2}{r} = \frac{\Phi_1 - \Phi_2}{n}$ (where + applies to cyclonic and — to anticyclonic curvature). This equation is independent of the density,

and can therefore be used at any level. A table, a nomogram, or a gradient wind-line based on this equation has general application, no matter at what level the charts are drawn. In the calculation made here, a nomogram has been used which has been worked out by Berg (1934).

The trajectories calculated in this way must necessarily be only approximate. The height-charts have been based on one series a day, and when calculating trajectories for one day and night at a certain level only two charts are available. In certain cases one can draw charts by interpolating between two given charts, and at the same time take into consideration intermediate ground charts, about which more is known. The possibility of error increases, the greater and more irregular the changes of pressure become. Under stationary conditions or when the changes of pressure are relatively regular it would appear that the method can be used with success. In this case it must, however, be taken into consideration that vertical movements of air occur. In order to achieve clarity regarding vertical movements, we have studied the wet-bulb potential temperature and assumed that it is a quasi-conservative property of the air. It is independent of adiabatic changes, except in the case of those which have been discussed above in connection with Refsdal's adiabatic paper. The temperature and the wet-bulb potential temperature may be changed by radiation. According to Möller (1935) this change of temperature does not exceed 1° C per 24 hours, i. e. still less in the wet-bulb potential temperature. We have consistently disregarded the effects of radiation. An increase of the wet-bulb potential temperature may arise from a vertical mixture in an unstable maritime polar air mass, without a general downward vertical movement taking place. In certain cases this effect can be considerable. Thus Willett (1935) calculated that the temperature rose by 20°—30° C in 36—48 hours when an arctic burst of air took place over the Gulf of Mexico. The conditions in Europe in April showed no such temperature contrast and we regard the heating by this means as inconsiderable.

One can make use of the humidity mixing ratio when studying air-movements. The humidity mixing ratio is not altered by adiabatic or non-adiabatic changes as long as water is not separated in the form of cloud or precipitation, or is absorbed in the air mass by evaporation. Hann-Süring (1939) assumes, on the basis of observations carried out by Conrad (1907) and Köhler (1927) among others, that the air can contain at the most as much water in drop form as in the form of vapour.

Bergeron (1935) assumes that water in the form of drops in certain cases, as in piled up Cb-clouds, can amount to three times the quantity of water in gas form, and Findeisen (1938 A) supposes that a still larger quantity of water in the form of drops can occur. The few measurements hitherto made have never shown higher values than those indicated by Hann-Süring. If we start out from Hann-Süring's statement, and disregard the cases where Cb-clouds occur, we can calculate an upper boundary for the upward motion in cases when rain has not been precipitated in the regions passed by the air. A downward movement can be approximately calculated from the mixing ratio, under the assumption that no water has been precipitated or taken up.

By combining the studies of calculated trajectories, wet-bulb potential temperature,

humidity mixing ratio and amount of precipitation, a certain reliability in the calculations can be obtained in cases where the figures correspond. If the calculations are not in accordance with each other, some new explanation must be given. Such an explanation is, for instance, that in certain cases the deviations from the gradient wind equation are considerable.

In the gradient wind equation the acceleration in the tangential direction of the course and the vertical acceleration have been disregarded. However, this may not always be done. In earlier works (Bjerknes and Palmén, 1938; Nyberg and Palmén, 1942) it has been shown how a deviation from the gradient has occurred, and below in the description of the weather on 21st.—22nd. April another example will be given. Judging from existing upper winds the deviations from the gradient wind are generally insignificant, but it is to be observed that in the actual regions where great pressure falls or strong accelerations or retardations occur, wind observations in higher layers of air are scanty. This is explained by the great amount of cloud in these regions. It is therefore only in exceptional cases that one has previously been able to determine empirically deviations from the gradient wind, but it is already possible that, by means of radiolocation of balloons, we shall be able to measure the real wind so accurately that such deviations can be calculated even when the sky is overcast.

## Fronts and Air Masses.

In a letter to NATURE, V. Bjerknes (1920) gave a description of the general atmospherical circulation as the meteorologists in Bergen, J. Bjerknes, H. Solberg and T. Bergeron, viewed it. The ideas which were put forward influenced most investigations in synoptical meteorology during the subsequent years. According to V. Bjerknes, a demarcation line or polar front, between air of tropical and air of polar origin, ran round the surface of the earth. A year earlier J. Bjerknes (1919) had already described the first polar front cyclone and described the upward gliding motion of warm air over cold air at the steering line, as well as the elevation of warm air by cold air at the squall line. J. Bjerknes and H. Solberg (1921) introduced the terms warm-front and cold-front, which were later adopted.

In »Wellen und Wirbel» Bergeron-Swoboda (1924) made a clear air mass classification between tropical and polar air. If the air mass was connected with a sub-tropical high-pressure area, on the south side of which trade winds immediately began, it was termed tropical air (**T**). Polar air (**P**) was defined as air which more or less directly originated from polar cold-reservoirs. Statistical material which was based on barely 20 soundings a month in Holland served as an indication that this classification was aerologically motivated (Bergeron, 1928). In his investigation Bergeron used the absolute temperature and the potential temperature. He also introduced the term arctic air (**A**), which according to Chromow's (1940) definition comes directly from arctic cold-centres, whereas the term polar air would only refer to air from the temperate zone. Bergeron (1930) intro-

duced, in addition to the polar front, the arctic front as a new main front at a mean latitude 65°—75° N separating polar air from arctic air.

Schinze (1932 and 1938) has, with abundant material, carried out an investigation of the «äquivalentpotentielle Temperatur», and later [Chromow (1940)] also of the pseudo-potential temperature (equivalent to the wet-bulb potential temperature). As a result he has obtained typical figures for **T**, **P** and **A**, from which the deviations should be small. However, the material has not been published in such a form that the size and number of the deviations can be judged. In later synoptic investigations it has often been found difficult accurately to refer the investigated air masses to the main air masses with the aid of characteristic values. For this reason many research workers have started to introduce new terms for air masses, and the number of these tends to increase. It is the author's opinion that air masses are best characterised by their physical qualities, and as a rule little is won for synoptic analysis by classifying them and introducing them into complicated systems. There are all types of transition between extremely warm air masses, which for a long time have been lying in sub-tropical high pressure areas, with centres towards the Equator, or which have come from the actual equatorial regions into the sub-tropical zones and from these into temperate regions, and cold air masses which have been formed at the hemisphere's cold pole and flowed towards the warm air masses. The observations of April 1939 within the temperate zone do not indicate, that the temperatures or wet-bulb potential temperatures accumulate around certain values (see Tab. V). Not even the observations from Angra and Carimaré show the constancy of temperature readings which might be expected, as these places are situated within the sub-tropical high-pressure area, which is the source of tropical air. This may possibly be connected with the fact that the high-pressure area is unusually mobile during the month in question, and at times lies very far to the north. J. Van Mieghem and L. Dufour (1942) have also found comparatively large variations in the temperature of tropical air, in an examination of the observations from Carimaré (1938). On the whole, however, the variability at Carimaré and Angra is fairly small, and much less than in Sweden. This is, of course, largely due to the position of the stations in the middle of the ocean, and also to the fact that the winds are much less powerful than further to the north. It is also nearest sea level that the values most tend to accumulate. The air attempts to assume the temperature of the surface of the sea. It is probably on this fact that the opinion is based which assumes that the air mass as a whole rapidly adopts a certain characteristic temperature within the high-pressure area, which would create a uniform tropical air mass. In reality the change in higher layers of air is slow, and the air mass which has gone practically all the way around the high-pressure area can, in spite of this, have a fairly low temperature. Humidity also changes very slowly in stable or indifferent stratification. According to Giblett (1923) an originally absolutely dry air mass which has flowed a hundred miles over the sea through indifferent stratification attains the relative humidity of 30 % in 1 km. It would seem to be a general rule that air masses in higher layers of air seldom stay so long at one place that they become independent of their previous history. In addition

*Table V.* **Frequency of Wet-Bulb Potential Temperature in April 1939.**

Angra N 38° 29′, W 27° 14′

| gkm | 6° | 7° | 8° | 9° | 10° | 11° | 12° | 13° | 14° | 15° | 16° | 17° | 18° | 19° |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | — | 1 | 1 | 1 | 1 | 3 | 6 | 4 | 2 | — | — | — | — | — |
| 1 | — | — | 2 | — | 1 | 1 | 3 | 8 | 1 | 1 | 2 | — | — | — |
| 2 | — | — | 1 | 2 | 1 | — | 3 | 4 | 4 | 2 | 1 | — | — | — |
| 3 | — | — | 1 | 1 | — | 2 | 3 | 2 | 5 | 3 | 1 | — | — | — |
| 4 | — | — | — | — | 2 | — | 2 | 4 | 6 | — | 2 | 1 | — | — |
| 5 | — | — | — | — | — | 2 | — | 2 | 7 | 3 | 1 | 1 | — | — |
| 6 | — | — | — | — | — | — | 1 | 2 | 4 | 2 | 5 | 1 | — | — |
| 7 | — | — | — | — | — | — | — | — | 3 | 5 | 1 | 3 | 1 | — |
| 8 | — | — | — | — | — | — | — | — | 1 | 2 | 4 | 2 | 1 | 1 |
| 9 | — | — | — | — | — | — | — | — | — | — | 2 | 3 | 1 | 1 |

Östersund N 63° 11′, E 14° 39′

| gkm | −3° | −2° | −1° | −0° | +0° | 1° | 2° | 3° | 4° | 5° | 6° | 7° | 8° | 9° | 10° | 11° | 12° |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 1 | — | 7 | 6 | 2 | 2 | 1 | — | 1 | — | — | — | — | — | — | — |
| 1 | 1 | 4 | 2 | 4 | 3 | 2 | 1 | 2 | — | 1 | — | 1 | — | — | — | — | — |
| 2 | — | 1 | 3 | 4 | 3 | 1 | 2 | 3 | 2 | 1 | 1 | 1 | — | 1 | — | — | — |
| 3 | — | — | 1 | — | 6 | — | 1 | 2 | 2 | 2 | 1 | 2 | — | — | 1 | — | — |
| 4 | — | — | — | — | 1 | 1 | 4 | — | 2 | 1 | 3 | 2 | 1 | 1 | 1 | — | — |
| 5 | — | — | — | — | — | — | — | — | 2 | — | 1 | 3 | 1 | — | 2 | — | — |
| 6 | — | — | — | — | — | — | — | — | — | — | — | 1 | — | — | — | 1 | — |

Carimaré approx. N 40° 00′, W 17° 30′

| gkm | 6° | 7° | 8° | 9° | 10° | 11° | 12° | 13° | 14° | 15° | 16° | 17° | 18° | 19° |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | — | 1 | 2 | 2 | 3 | 8 | 6 | 4 | 1 | — | — | — | — | — |
| 1 | 2 | 2 | 2 | 2 | 2 | 9 | 3 | 2 | 2 | 1 | — | — | — | — |
| 2 | — | 2 | 2 | 3 | 3 | 4 | 4 | — | 3 | 2 | 2 | — | — | — |
| 3 | — | — | — | — | 1 | 6 | 5 | 2 | 2 | 3 | 2 | — | — | — |
| 4 | — | — | — | — | — | 3 | 6 | 4 | 1 | 4 | 1 | — | — | — |
| 5 | — | — | — | — | — | 1 | 4 | 7 | 1 | 4 | 1 | 1 | — | — |
| 6 | — | — | — | — | — | — | 2 | 4 | 3 | 3 | 3 | 1 | — | — |
| 7 | — | — | — | — | — | — | — | 1 | 5 | 1 | 2 | 2 | 1 | — |
| 8 | — | — | — | — | — | — | — | — | — | 2 | 2 | — | 2 | — |
| 9 | — | — | — | — | — | — | — | — | — | 1 | — | 3 | — | 2 |

Stockholm N 59° 21′, E 17° 57′

| gkm | −3° | −2° | −1° | −0° | +0° | 1° | 2° | 3° | 4° | 5° | 6° | 7° | 8° | 9° | 10° | 11° | 12° |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | — | — | — | 4 | 3 | 2 | 2 | 1 | 1 | 1 | — | — | 1 | — | — | — | — |
| 1 | — | — | — | 2 | 3 | 1 | 3 | 3 | — | — | 2 | — | 1 | — | — | — | — |
| 2 | — | — | — | 1 | 1 | 3 | 2 | 3 | — | 1 | — | 2 | 1 | 1 | — | — | — |
| 3 | — | — | — | — | — | 1 | 4 | 1 | 3 | — | 2 | 2 | 1 | 1 | — | — | — |
| 4 | — | — | — | — | — | — | 1 | 2 | 4 | — | 2 | 2 | 2 | 1 | — | — | — |
| 5 | — | — | — | — | — | — | 1 | — | 3 | 1 | 1 | 4 | 1 | — | 2 | — | — |
| 6 | — | — | — | — | — | — | — | — | 1 | 1 | 1 | 2 | 1 | 2 | 1 | 2 | — |
| 7 | — | — | — | — | — | — | — | — | — | — | — | — | — | 3 | — | 1 | 1 |
| 8 | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | 2 | 1 |

to this the position of the high-pressure area varies considerably. Sometimes its centre is at the Canary Islands and sometimes as far north as Ireland. The air masses which limit the polar front at the south thus have a temperature which varies considerably from place to place, and the same can be said of the air masses north of the polar front and of those south and north of the arctic front. Nevertheless in all cases we will retain the terms **T**, **P** and **A** for conventional and historical reasons, whilst pointing out that the use of these terms involves a relatively large degree of arbitrariness.

## A Ground-Synoptic Survey.

### The Construction of Ground Charts.

The synoptic ground charts have been based on the working charts regularily made at the Meteorological-Hydrological Institute of Sweden, Stockholm. The charts have then been checked and supplemented, partly by observations and bulletins which have been received by the Institute, and partly by observations which were sent to the Institute by special request. (A list of these is to be found in Bibliography B). On the published charts for 0700 hours GMT only a small number of observations have been included on account of the limited space. The observations have been drawn in accordance with the station model (Fig. 6) where the terms are those generally used; see, for instance, Publ. Nr.

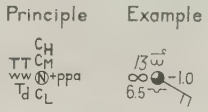



Fig. 6. Station model.

29 des Secr. du O.M.I. p. 194. It must, however, be observed that the letter $T_d$ represents the dew-point, which, according to an investigation by Petterssen (1939), can be regarded as most suitable for identifying air masses at ground level.[1] Fronts and air masses have been characterised by the symbols recommended by the International Meteorological Organisation (1936). The less clear fronts have been drawn without communicating lines between the points. In drawing the fronts consideration has always been taken to the analyses made by the weather bureaux of Stockholm, Oslo and Deutsche Seewarte, Hamburg, as they have appeared on working charts and published bulletins. As a rule these analyses show satisfactory agreement. The analyses chosen by the author in each special case in general agree with the aerological observations, but it is obvious that in most cases greater or smaller variations are possible in the analyses made. Especially over the sea, where observations are few, the possible renderings are many. The author has as a rule tried to draw the ground front patterns as conventionally as possible in

[1] On the ground charts the pressure tendency under increasing pressure has been termed $S_a$, and under decreasing pressure $F_a$. The index $a$ indicates the size of the pressure change in millibars in three hours.

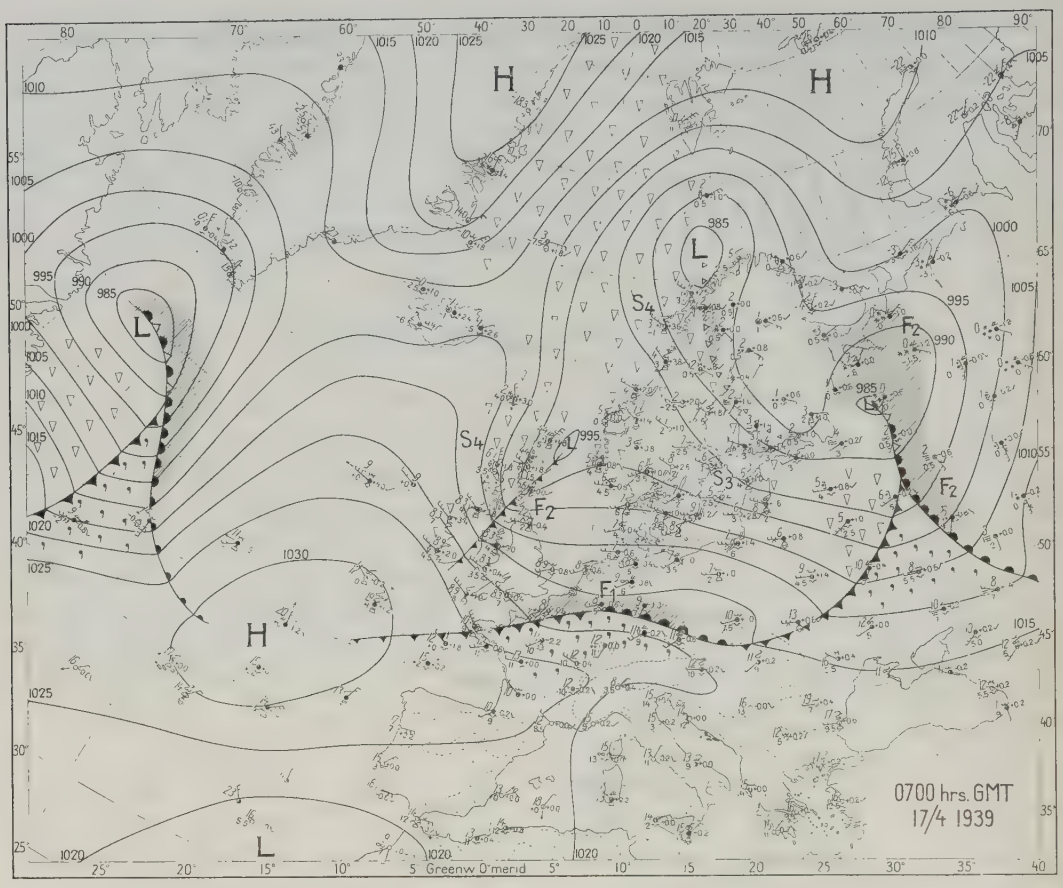



Fig. 7. Weather chart (ground chart) for 0700 hrs. GMT on April 17th. 1939.

connection with Chromow's textbook and T. Bergeron's lectures, and wishes to underline that this investigation is not ground-synoptic, but has mainly been concerned with the conditions in higher layers of air. For this reason the survey of the ground-synoptic situation has been made relatively brief.

### April 17th.

On April 17th. there is a depression with its centre east of Onega. A cold-front runs from the point of occlusion in the neighbourhood of Moscow towards the south-west, and can be faintly observed north of Budapest; to the west of it a wave has apparently formed on the front, the most northerly position of which is approximately at Cologne. After this the front runs as a cold-front in a west-south-westerly direction and disappears in the Atlantic high-pressure area, the centre of which is situated north-east of the Azores.

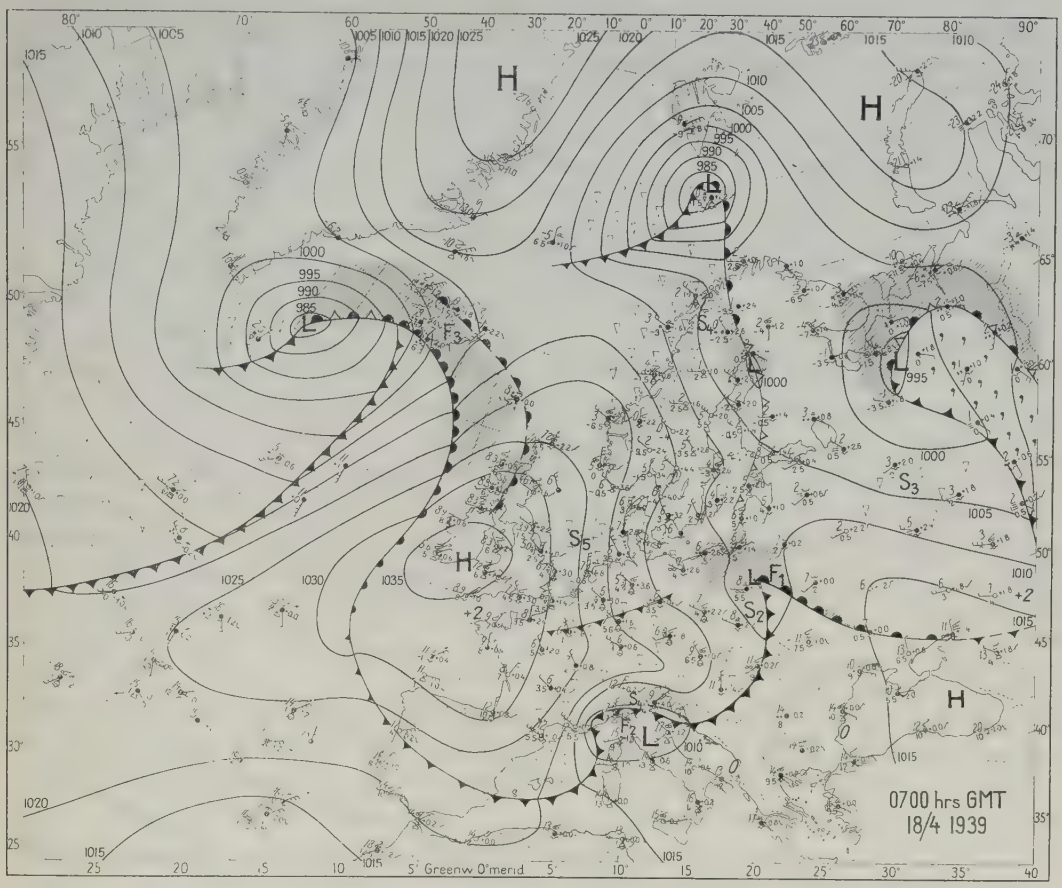



Fig. 8. Weather chart (ground chart) for 0700 hrs. GMT on April 18th. 1939.

South of Greenland there is a low-pressure area which causes a powerful warm air advection in the district south of Iceland. The positions of the fronts associated with this low pressure area are fairly uncertain. Above the Faroe Islands and to the east of them there is a powerful northerly current by which fresh polar air or arctic air is carried southwards. A front between this air mass and a warmer polar air mass south of it can be observed over England. In the low-pressure trough above Finland and North Scandinavia some precipitation occurs, but a possible front seems to be only faintly developed.

**April 18th.**

The low over Russia has moved slightly in a north-easterly direction. A warm-sector is situated outside the region of the chart, whereas the occlusion front and its back-bent front form an apparent warm-sector. The wave formation which was observed above South-West Germany on the 17th. now lies over Poland and has developed into

a closed but weak low, with a distinct precipitation area. From here the cold-front goes to the south towards Italy where a low-pressure area has developed to the leeward of the Alps. Over Western Germany the boundaries of the fresh polar air can still be observed, but the front is decidedly less marked than on the previous day. The Atlantic high-pressure area has moved to the north-east, and over the Atlantic between Iceland and Scotland a powerful advection of warm air prevails. The position of the main warm-front connected with the low pressure south-west of Iceland is difficult to determine from ground observations. The position of the cold-front is more definite. A second warm-front which is assumed only to reach the height of a few kilometres can be vaguely discerned hardly 500 km. in front of the main warm-front, partly on account of the fact that the temperature at Thorshavn has a value of $+9°$ long before the main warm-front at the ground, while at the same time at the same latitude a temperature of $+3°$ was measured on the west coast of Norway.

While the warm air flows to the north-east in the south-west regions of the Norwegian Sea, cold air (arctic air) is carried southwards in its northern part, to the west of the deep low-pressure area between Spitzbergen and Northern Norway. On account of this, the contrasts of temperature in the region are intensified to a large extent the following day. The flow is typical of frontogenesis, according to Bergeron (1928).

**April 19th.**

The depression developed from the wave formation is to be found over Central Russia. It has deepened to approximately 1 003 mb. To the west of this low, cold air pours down through Central Europe towards Greece and Italy. The anticyclone over the British Isles has moved still more towards the north-east, and on its south side colder air is carried westwards and is heated over the Bay of Biscay and the Atlantic. In the north, the low from the region west of Iceland has moved fairly rapidly to the east, and now lies between Jan Mayen and Northern Norway. A considerable increase in depth has not occurred during the last 24 hours, but at 0700 hours GMT the falling tendency is very great, — 7.8 mb. in three hours at Lofoten. The plotted northern warm-front appears to be identical with the secondary warm-front of the 18th. April, whereas the southern one is identical with the main warm-front of the 18th. The ground observations are few, and completely different analyses are also possible, but the above rendering agrees best with the results gained from the aerological analysis. Towards the south, near the high-pressure area, the warm-front becomes more and more diffuse. The cold-front has not yet reached Thorshavn. To the west of the Azores there is a low-pressure area which possibly has a frontal connection with the cyclone in the north. In the low-pressure trough which runs west-south-west from this northern cyclone there is a frontal zone which may be called the arctic front.

**April 20th.**

There is a low-pressure area over the South-East of Russia and to the west of it cold air continues to flow southwards. Nearer the English high-pressure area there is an ad-

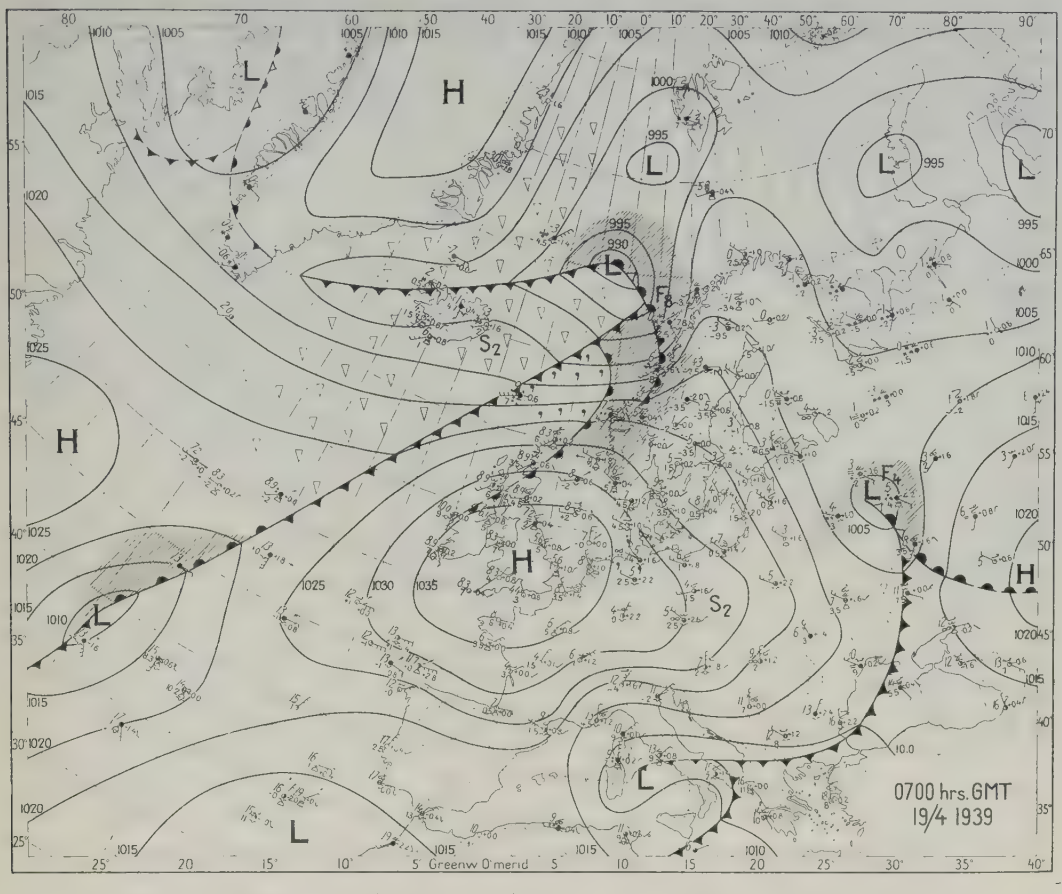



Fig. 9. Weather chart (ground chart) for 0700 hrs. GMT on April 19th. 1939.

vection of warmer air, but a warm-front is difficult to discern in the high-pressure area. Not until further to the north in Latvia and Esthonia do we find that an upward gliding motion occurs, and true warm air advection prevails. The warm air flows more rapidly to the east in the northern parts of the disturbance and the result of this is that the cold air over South Russia is cut off during the next 24 hours, a phenomenon which can only be faintly seen in the ground charts, but which is all the more clear in the height-charts.

The cold-front connected with the warm-front is less distinct, and its position cannot be determined through ground observations. It appears to form a wave over South Norway, and thence runs to the south-west and continues as on the previous day into the low-pressure area over the Azores. The English high-pressure area has become weakened from 1038 mb. on the 19th. to 1033 mb. on the 20th., and has at the same time moved to the south. The depression over North Finland has deepened to approximately

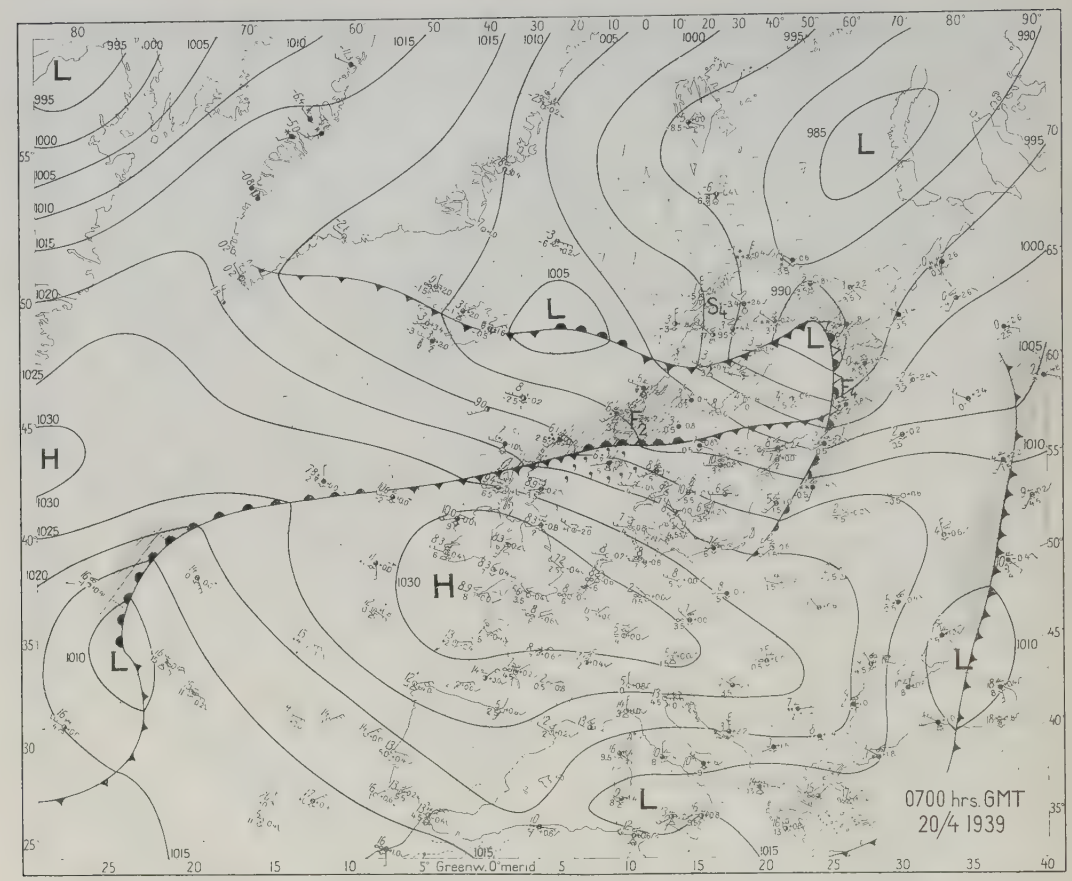



Fig. 10. Weather chart (ground chart) for 0700 hrs. GMT on April 20th. 1939.

988 mb. in its movement from the west. The front which runs from its centre west-south-west can be regarded as a back-bent occlusion; it has at the same time distinct cold-front character, and is identical with the arctic front of the previous day. As far to the west as over Iceland the arctic front can be traced, but there a general rise of pressure prevails on both sides of the front, which is gradually frontolysed.

### April 21st.

The pronounced low in North Europe is beginning to be filled out in the course of its progress eastwards. A wave disturbance which lay over South-West Norway on the previous day is now to be found over the Baltic States; the fronts are less distinct, but a continuous rain area appears clearly at the warm-front. The arctic front has disintegrated since the day before. Between the fresh polar air over Sweden and the warm air in the anticyclone over France there is no distinct front at ground level. The showers

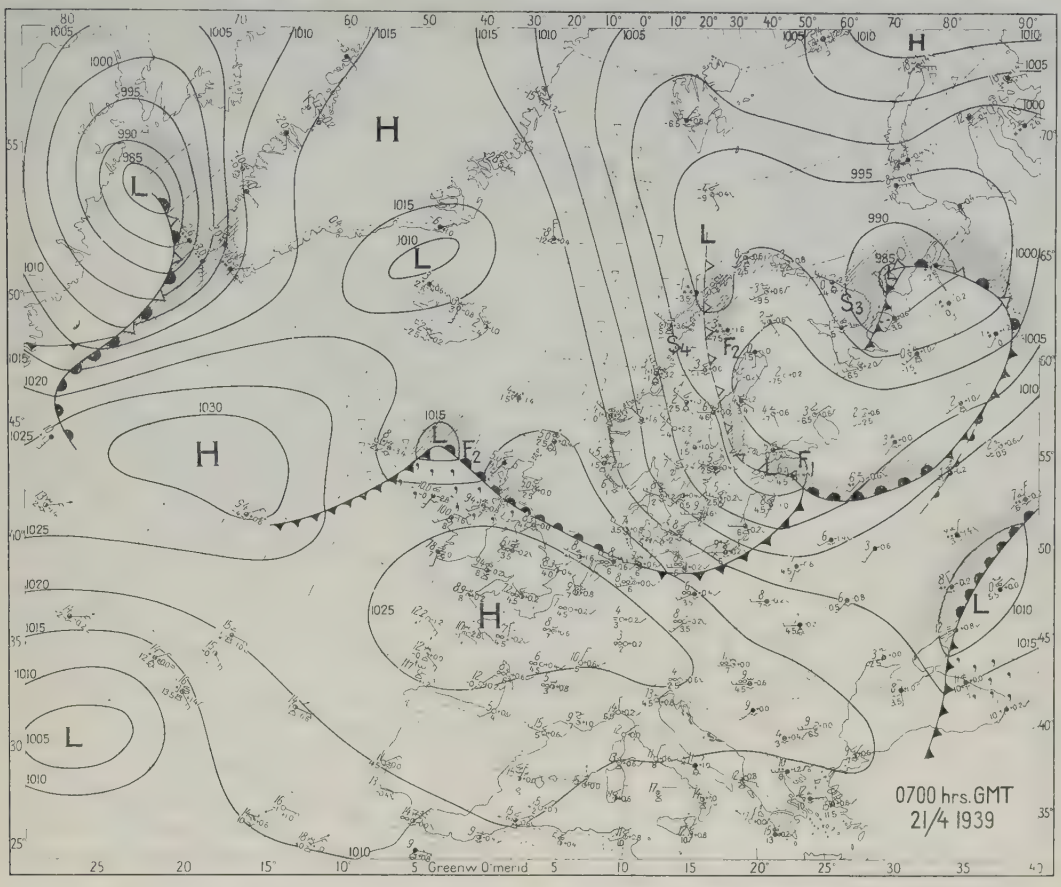



Fig. 11. Weather chart (ground chart) for 0700 hrs. GMT on April 21st. 1939.

over Sweden, however, indicate lability and cold at a high level, whereas stability and warmth prevail at a high level in France. In Scotland the hydrometeors, the wind and the pressure tendencies indicate a warm-front, and the pressure distribution indicates that there is a new wave disturbance to the west of this. The anticyclone over Northern France and South England has been reduced to 1028 mb. at its centre, and has moved still more to the south. At 50° N 35° W a new anticyclone is growing, the pressure of which already exceeds 1 030 mb., and which contributes to the deepening of the wave disturbance as it brings down cold air at the rear of the newly formed cyclone.

Over South-West Russia cold air still remains, whereas the temperature to the east of the low-pressure trough at the Lower Volga has risen some degrees. The air lying at 55° N, which has been carried from the west and which was comparatively warm some days earlier, has now been cooled by radiation so that, at ground level, it has the same temperature as the cold air in South-West Russia, or is even colder.

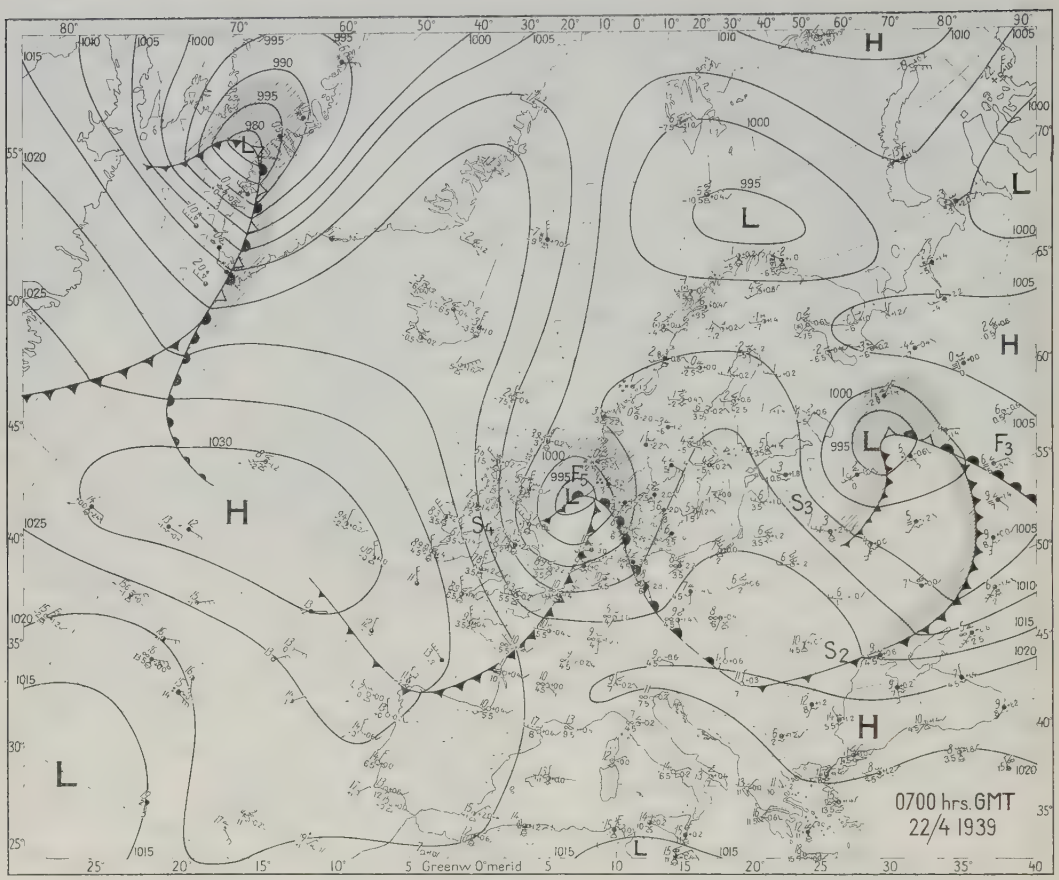



Fig. 12. Weather chart (ground chart) for 0700 hrs. GMT on April 22nd. 1939.

In the cold air trough over North Scandinavia precipitation occurs at several places. It is preceeded by a 2 mb. pressure fall in 3 hours and is followed by a rise of 4 mb. in 3 hours. A distinct ground front can, however, not be found. The temperature is actually higher to the west of the trough in a strong north-westerly current.

### April 22nd.

The depression over the Baltic States of the 21st. has deepened to 993 mb. and is situated 700 km. further to the east. The cold-front is characterised by a distinct wind discontinuity and, in certain regions, by altostratus and rain. In the warm sector which contains some of the cold air which on the 21st. was to be found to the west of the Black Sea, the stratification is unstable, and Cb-clouds are reported from Stalingrad at 0700 hours GMT (1000 hours local time). The relation of the cold-front to the warm-front associated with the low-pressure area over the North Sea is indefinite, nor can the position of the warm-front be determined. The cyclone which has arisen out

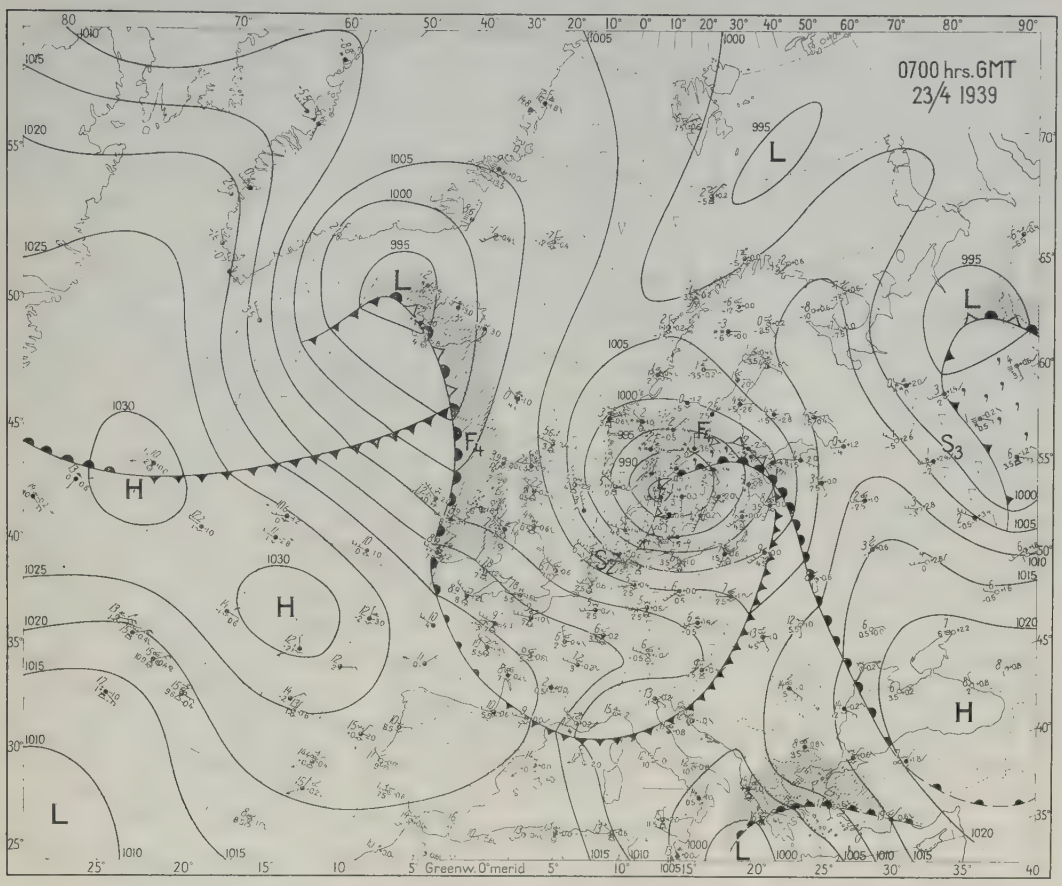



Fig. 13. Weather chart (ground chart) for 0700 hrs. GMT on April 23rd. 1939.

of the wave disturbance to the west of Scotland on the previous day, has a pressure of 990 mb. at its centre, as compared with 1 010 mb. on the 21st., and it is still growing deeper. West of the centre, cold air is rapidly flowing southwards and a cold-front is passing over the west of Belgium and France. The Atlantic anticyclone at lat. 50° has increased in strength. The pressure at the centre amounts to approximately 1 035 mb. At Baffin Bay there is a deep low-pressure area and an accompanying occlusion-front runs through the south point of Greenland southwards to the occlusion point at approximately lat. 57°. Between Southern Greenland and Iceland warm air advection prevails, while east of Iceland arctic air flows southwards. Jan Mayen has —7° and snow squalls. A tendency to frontogenesis south-east of Iceland is clear.

### April 23rd.

From North-Eastern Russia the material from observations is especially scant and the analysis is therefore uncertain. Over the Black Sea a high-pressure area has formed.

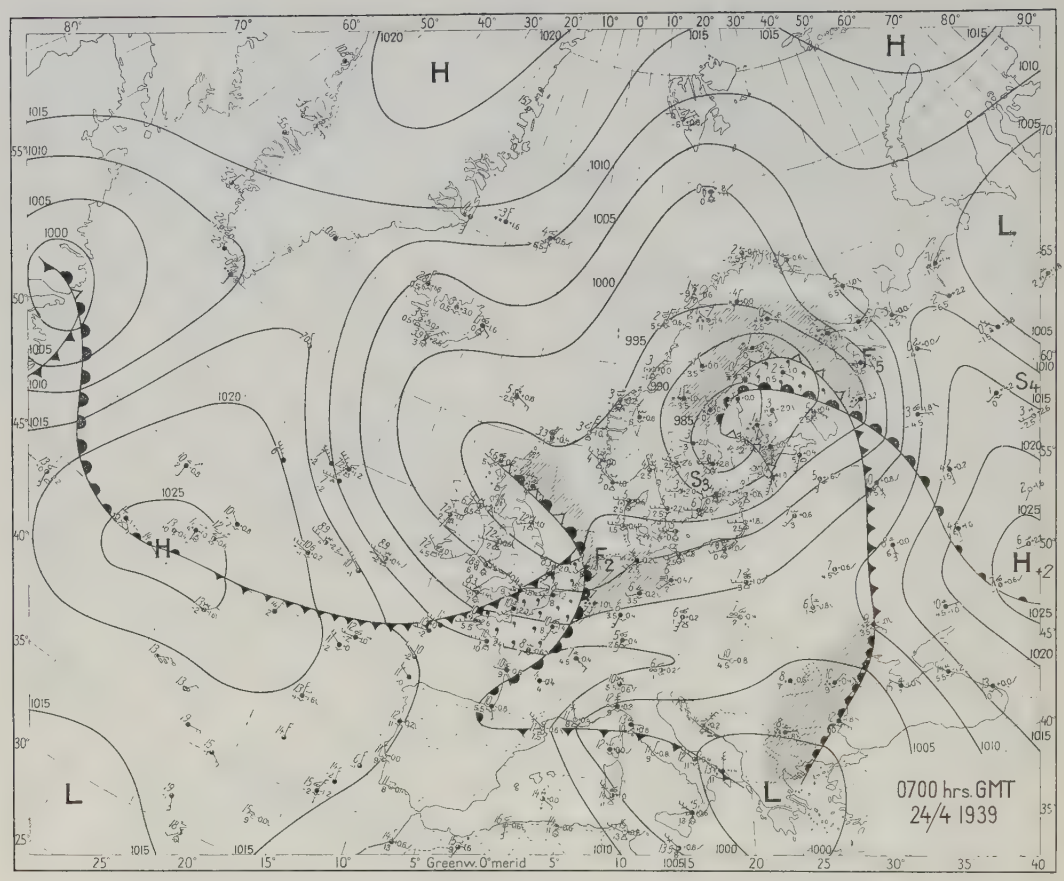



Fig. 14. Weather chart (ground chart) for 0700 hrs. GMT on April 24th. 1939.

Between this high-pressure area and a low-pressure area south-west of Sicily there is an advection of very warm air into the old warm sector. In the morning 24° was recorded on Crete.

Since the previous day the low-pressure area over the North Sea has moved to the east; its centre is near Gothenburg. Since the wave disturbance was first observed 48 hours earlier, the pressure minimum has fallen from approx. 1 012 mb. to 978 mb., i. e. approx. 35 mb. The deepening continues, and the cyclone moves to the north-east. In the depression can be laid the upper cold-front and ground warm-front, which were included in Bergeron's cyclone model (Bergeron 1937 and Chromow 1940). These fronts have been plotted on the chart, although the author will not claim that the correctness of this analysis has been proved by the observations. We will return to this question in the analysis of the height-charts. South of the occlusion point the warm-front can be found, especially with the aid of temperature readings. The position of the cold-front

in the Adriatic Sea can be determined in the same way, as well as by reports of thunder and hail. The continued course of the front is uncertain, as is the whole frontal system related to the Icelandic low-pressure area. In this, however, the warm-front is determined by the position of the precipitation area over Ireland and by some observations from ships. The Atlantic high-pressure area has been levelled out and fallen into two.

**April 24th.**

The observations from North-Eastern Russia are for this day also extremely sparse, and thus the analysis is approximate. The high-pressure area in South-Eastern Russia has increased, and now causes a warm air advection over Central Russia. The warm-front to the Scandinavian low-pressure area is visible in the temperature field, and so is the cold-front south of the point of occlusion. To the west of the Black Sea there is a region with typical rain caused by upward gliding motion in connection with the low-pressure area over Greece. In the western regions of this low-pressure area we see a low-pressure trough in which a faint cold-front has been drawn.

The filling out of the cyclone over Scandinavia has commenced, but there is still abundant precipitation, in the northern region as snow, showing general elevation of the air, in the southern region as showers, indicating an extremely unstable air mass. It is of interest to observe that on this day also Bergeron's occlusion model can be drawn, based entirely on ground-synoptic material. This has been done by the Weather service of the Meteorological-Hydrological Institute of Sweden.

Over Scotland and the North Sea a minor increasing low-pressure area can be observed. In front of the precipitation area of this low pressure a distinct wind discontinuity can be observed, followed by rising temperature and a somewhat increased fall of pressure. The aerological material shows to what a large extent the disturbance diverges from the pattern.

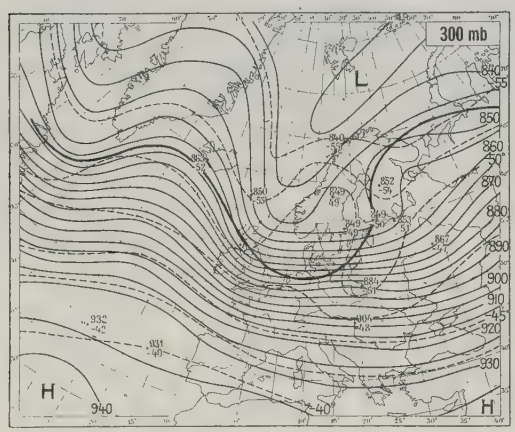
## Synoptic-Aerological Analysis.

**April 17th.**

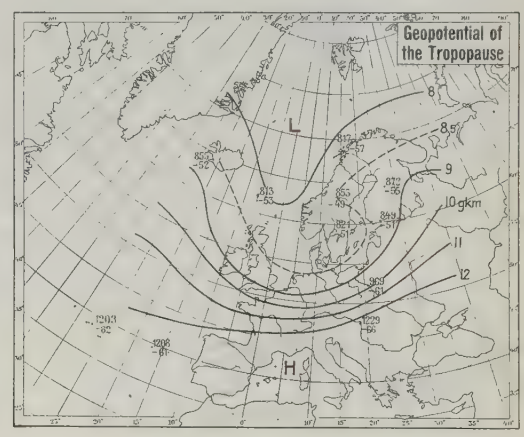
If one attempts to find the fronts which have been obtained from ground charts with the aid of meteorological analysis it does not always prove to be simple. The assumption that in a new cyclone the main part of the isobar-isosteric solenoid field, or even the whole of it, is concentrated to a front of small normal horizontal and vertical dimensions, has proved to be erroneous in several earlier investigations (Bjerknes and Palmén 1938). Let us put the following question: Are fronts actually a necessary condition for cyclogenesis? To this we reply in the negative. Cyclogenesis can occur if only a certain horizontal temperature gradient (i. e. a sufficient number of solenoids) is to be found in an area. This condition was fulfilled on April 17th., 1939 over Germany. Regarding the size of the temperature gradient and the extension of the area, the values are 1° per 100 km. and 1 000 km., but there are no direct reasons to assume that these values

are the limiting values. The conditions within the area are of a certain interest, as the number of investigations of frontal waves based on aerological material is small, and here is a case with comparatively many observations from higher layers of air. For this reason we will discuss the soundings in this area more closely.

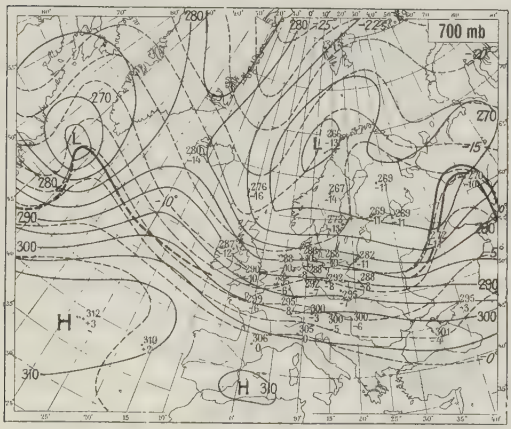
To start with, a few words about the Russian low-pressure area (Fig. 7 p. 30). We find there that the warm-front is indicated by the soundings at Syktyvkar at the level 1.9—2.5 gkm. Fig. 18 p. 46. (To all temperature-height curves in the diagrams a line corresponding to zero degrees has been drawn above the station figure up to the curve. When the temperature in all levels is below zero degrees this line has been drawn to 1 gkm. The relative humidity is shown in the figure when the change of humidity at each characteristic point is of significance and always if the change of humidity between two points exceeds 10 %.) Further to the south-east Orenburg has the temperature —9° at



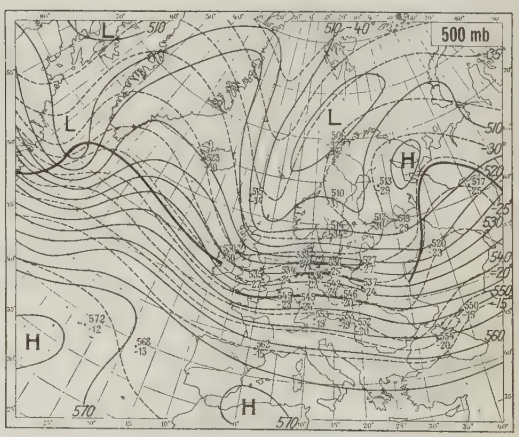

c) 300 mb.




d) the tropopause.




a) 700 mb.




b) 500 mb.

Fig. 15. Geopotential charts for April 17th.

700 mb. and Sverdlovsk has —15°, without a front being observed in the soundings. In Moscow (Fig. 18) the cold-front is found at the level 2.7—3.2 gkm. North-west of here the air mass indicated in the chart for 700 mb. (Fig. 15) is comparatively homogeneous within an area, the size of which is unusual in these regions.[1] South-west of Moscow the cold front cannot be observed, nor can its expected continuation as a warm-front further to the west. From the height-chart for 700 mb., we see how the temperature, disregarding

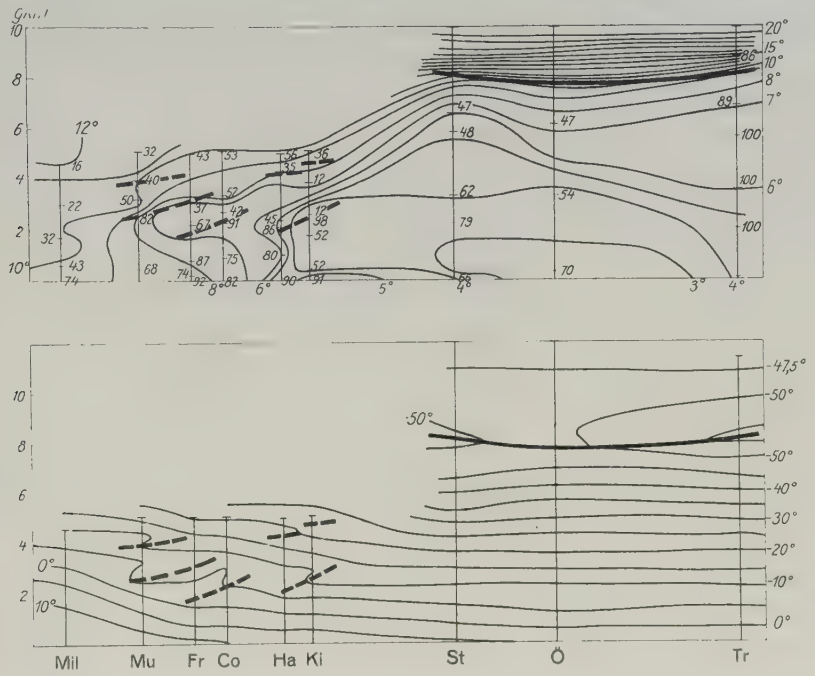



Fig. 16. Cross-sections showing the temperature (C) and the wet-bulb potential temperature on April 17th. 1939. Milan, Munich, Frankfurt, Cologne, Hamburg, Kiel, Stockholm, Östersund and Tromsö.

divergences connected with the heterogeneity of the air mass or chance observational errors, falls relatively continuously from Milan in the south to Königsberg in the north. The temperatures north and south of these places change only slightly with the latitude. Milan has 0°, Munich —3°, Vienna —5°, Paris —6°, Frankfurt, which is slightly too cold, —8°, Cologne —6°, Breslau and Berlin —7°, Lindenberg, Warsaw and Hamburg —8°, Norderney, Kiel and Warnemünde —10°, Königsberg —11°, Stockholm —13°, Östersund —14° and Tromsö —13°. The conditions are similar at the 500 mb. level. The soundings made from aeroplanes do not generally extend to that level and therefore have been extrapolated. It seems, however, certain that the accumulation of isotherms

[1] On the height-charts the geopotentials have been indicated in geodynamic dekametres, apart from the isogeopotential lines for the tropopause, which are given in gkm.

at high levels has been displaced in a northerly direction at the same time as the horizontal gradient has been strengthened in a south-north direction. Milan has approx. —15°, Munich —19°, Berlin —24°, Königsberg —27°, Stockholm —34° (slightly too cold?) and Tromsö —32°.

A cross-section Milan—Tromsö (Fig. 16) supplements the synoptic height-charts. The section includes the temperature (at the bottom of the fig.) and the wet-bulb potential temperature. The temperature is drawn for every five degrees, the wet-bulb potential temperature for each degree, slightly rounded off. The relative humidity is shown in the upper figure, when the change of humidity at each characteristic point is of significance, and always if the change of humidity between two points exceeds 10 %. Here,

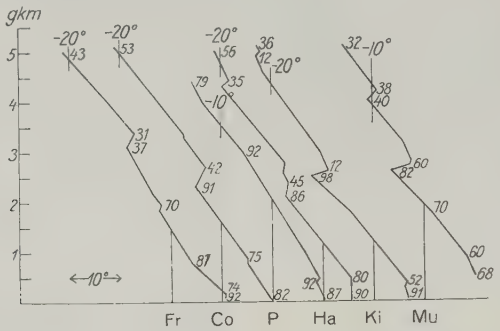



Fig. 17. Some temperature-height diagrams on April 17th. 1939. Frankfurt, Cologne, Paris, Hamburg, Kiel and Munich.

just as on the geopotential chart, the constancy of temperature from Stockholm northwards is striking. The humidity at Tromsö is high, and therefore the wet-bulb potential temperature is higher than at Östersund and Stockholm in the lower troposphere. From Stockholm southwards the temperature increases more rapidly.

If we wish to use the concept of air mass we can say that in the north there is an almost barotropic air mass **A** which has passed over the North Atlantic. To the south of this, without any sharp transition, a strongly baroclinic air mass **P** follows. This has a continued transition to maritime **T**. The inclination of the isotherms is especially great between Munich and Milan, which is connected with the fact that the air at Milan has fallen. The air there is very dry and the relative humidity falls below 50 % everywhere except at ground level. Between 2 and 4 gkm. the relative humidity is only 30 % to 20 % and at higher levels still lower. The isolines for the wet-bulb potential temperature naturally have a course which is opposite, more or less, to that of the isotherms. They are especially low in the south and high at Stockholm. In some districts the isopleths are sparse or have strikingly steep inclinations. It is obvious that in some layers the vertical temperature gradient is equal to, or larger than, the saturated adiabatic, at Kiel 0.4—2.5 gkm. and at Hamburg, 0.5—2.1 gkm., as well as at Cologne 0.9—2.3 gkm., Munich 0.9—2.6 gkm. and Frankfurt 0.2—1.9 gkm. See also Fig. 17. If the air was saturated with moisture the stratification would thus be moist-indifferent or moist-labile.

The humidity values in the layer in question only amount to 80—90 %. Considering the lag of the hygrometers and other errors the possibility of saturation is not excluded. An investigation of the reports in clear text from the aeroplane soundings, indicates the following clouds in the layers. Kiel: »1 200 m rings 8/10 quellender Sc, 2 400—2 700 m leicht quellender feuchter Sc». Hamburg: »ab 600 m 2/10 Sc». Cologne: »7/10 Sc 2 300—2 400 m». Frankfurt: »700—1 400 m 6/10 Sc leicht quellend». Munich: »Bei 2 000 m 2/10 Ac». From the reports on »quellender Sc», i. e. instability-clouds, we see that at least at Kiel and Frankfurt moist-lability prevails, whereas conditions are less certain at other stations.

From the 3 gkm. level the stratification in Germany is suddenly very stable. The temperature inversions are everywhere combined with decreasing humidity, indicating a considerable subsidence. The observations of clouds made by the crews of sounding-aeroplanes are excellent supplements to the results shown by the instruments. In the far north As-clouds are indicated above the max. level, i. e. 5 100 gm., whereas the subsidence is distinct in the 2 km. thick layer beneath it. At Cologne, Frankfurt and Munich lenticular clouds have been recorded, which proves the occurrence of general subsidence over the inversion area. The level of inversion is practically the same in the north and in the south. The picture of the aerological conditions is finally completed by the reproduced temperature-height curves, which have been drawn for certain selected stations. (Figs. 17—18).

The forming of precipitation is a question of special interest. In accordance with the frontal wave theory (see e. g. Chromow 1940 or V. Bjerknes et al. 1933) one would expect an upward gliding motion of air over that front surface, whose intersection with the ground the front was intended to represent. However, the relatively good aerological material shows that no real upslope front exists. The temperature inversion is an upper cloud limit, and precipitation is formed in the colder air below it.

It is remarkable that the air in the rain-forming layer is of moist-labile or moist-indifferent stratification. A similar stratification is also to be found in the region south of the ground front and even at a considerable height, as above Paris, where moist-indifference prevails up to the maximum altitude of the soundings, or 4.4 gkm. Rain falls, not only in the narrow area to the north of the ground front but also at several places to the south as at Stuttgart and Strasbourg. The clouds recorded are generally of an As- or Ac-character in the north, and Nb or Cu congestus south of the front. At Nurnberg, »showers» are reported, otherwise mostly »light continuous rain», on the ground chart schematically represented as drizzle. At some places glimpses of blue sky have been seen north as well as south of the front. When there is no height-front, and when an upward gliding motion along a warm-front surface is thus out of the question, we can assume a *general elevation* of the air within the area, which gives rain, especially north of the warm-front drawn.

At the most the elevation can continue up to the level of inversion; in and below this level divergence must prevail. The moist-labile or moist-indifferent stratification may have arisen from the elevation of an air mass which was originally stable, but in which

the wet-bulb potential temperature has fallen with the altitude. On account of elevation and possibly also vertical stretching, the vertical temperature-gradient has increased to the moist-indifferent or the moist-labile value. The higher air layer, which is assumed to have been comparatively dry, is cooled by elevation, and especially by vertical stretching, more than the moister air below, cf. Rossby (1932), von Ficker (1936) and Hewson (1936). The stratification in such an air mass may, according to Rossby (1932) and Normand (1938), be regarded as »conditional» or »convective instability». Hewson (1937) uses the term »potential instability».

With the material available at present, it is not possible to determine the causes of this elevation and its limits, which are indicated by the inversions.

Another explanation for the rain is the assumption that the indifference is actually a slight lability, which is partly hidden by minor errors in the observations. It would seem that the rain is due to an over-running of cold air at high levels, which occurs at a greater speed than at ground level. A large number of authors have treated different cases where precipitation, in their opinion, has been caused by rapidly moving cold air at high levels. (Douglas 1929). This phenomenon has been regarded as specially distinct in connection with the formation of thunder at cold-fronts (Reidat 1930). Of the remaining works in this field, we shall only mention one, Putninš (1942), in which references are made to a large number of earlier investigations.

With the material at present available to aerologists, it is very difficult to determine whether the above-mentioned rapid current of cold air exists. The courses of isotherms and isobars are usually so uncertain that one cannot determine whether the advection quantity $\left(\frac{\partial T}{\partial t}\right)_h = -\left(v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y}\right)$, calculated from isothermal distance and gradient wind, is larger at one level or at another. In addition to this, deviations from the gradient wind may occur. Of still more importance are the vertical air movements. We calculate $\left(\frac{\partial T}{\partial t}\right)_h$ at two levels. At the lower level the component of the gradient wind at right angles to the isotherms is 14 m. per sec., at the higher level the corresponding velocity is 28 m. per sec. The distance between the isotherms (for 1°) is 100 km. at both levels. $\left(\frac{\partial T}{\partial t}\right)_h$, the horizontal cooling off per hour, is 0.5° and 1.0° respectively, and the vertical difference of temperature would thus increase by 0.5° per hour above the locality in question, which would cause instability. We assume that the air at the higher levels is in downward motion with a speed of 2 cm. per sec. or 72 m. per hour, i. e. approx. 1 600 m. per 24 hours, which is a reasonable speed (see, for example, 19th. April below, p. 63). At the same time the air at the lower level is assumed to move horizontally. Then the air at the higher level will be heated adiabatically by 0.5°—1.0° per hour, depending on the degree of humidity, and the temperature. Thus, on account of this vertical motion, the temperature at the higher level will not fall more rapidly than at the lower one, in spite of the horizontal advection effect, and the stable conditions will not be changed.

When instability occurs we are accustomed to expect Cb-clouds, or at least typical convection-clouds. As has been mentioned, principally stratiform clouds were reported in the case under observation, although Cu congestus were reported at several places to the south. Is it, indeed, possible that stratiform clouds can be formed by rapidly moving cold air? We suppose that this is the case. If labilisation proceeds very slowly, but continually, it would appear that a close bank of clouds can form, in which case a fairly regular precipitation of water will occur. The downward air movements may be regarded as distributed over large regions. In this case the speed and downward motion become so small that the clouds formed do not completely disperse. If the depth of the labile air mass is small, the speed of the upward air currents becomes insignificant; as the masses moving in a downward direction are smaller, light rain may be precipitated, sometimes intermittently, without the clouds disintegrating to any large extent. On April 17th. the situation is such, with gaps in the clouds and intermittent rain, that it does not seem improbable that the precipitation is caused by rapidly moving cold air at high levels. On account of the development and the conditions on the following day, it seems, however, more probable that the precipitation is caused by general elevation of the air at lower levels.

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The cold-front over Scotland is probably a phenomenon which does not extend high into the atmosphere. At Thorshavn there is, at a level of 1.6 gkm., a discontinuity in the sounding curve (Fig. 18). Below this point the lapse rate is very large, no doubt a consequence of the heating of the air in passing over warm sea-water. The point of discontinuity should thus indicate the level to which the heating effect of the sea has reached through convection, while above it there should be a more undisturbed air mass. At a considerably greater height, 5.3 gkm., there is at Thorshavn yet another discontinuity, which may be assumed to be an upper boundary for the cold air flowing from the north (**A**) and an air mass coming from a more westerly direction (**P**). The fact that the direction of flow is more or less uniformly northerly does not prevent an earlier air mass boundary from persisting for some time. Reykjavik shows two similar layers at 0.6 gkm. and 5.9 gkm. which may be regarded as formed in the same way. It is therefore reasonable that the upper isothermal layer at Reykjavik is less pronounced than that at Thorshavn, where the arctic air current is more powerful. At Reykjavik a warm-air advection is already beginning to appear, the temperatures at 700 mb. and 500 mb. being —14° and —30°, as against —16° and —34° at Thorshavn. This advection is caused by the low-pressure area between Labrador and the south point of Greenland, which reaches a high level and supports a south-westerly air current over the North-West Atlantic.

The chart for the 300 mb. level (Fig. 15) gives us an idea of the maximum strength of the upper-wind, which is to be found at the tropopause level at or near the 300 mb. level. The chart shows a thick unbroken line which represents the intersection of the 300 mb. level with the tropopause; to the north of this line the wind generally decreases

with the height, and to the south it increases somewhat up to the level of the tropopause. At this level the contrasts of temperature are smaller than at lower levels. The extreme temperatures recorded at levels represented on the chart are, at the 700 mb. level, Angra + 3°, Thorshavn —16° (difference 19°), at 500 mb. Angra —12°, Thorshavn —34° (difference 22°), at 300 mb. Carimaré —40°, Tromsö —55° (difference 15°). At 200 mb. the difference is greater again, and there it is coldest in the south, Angra

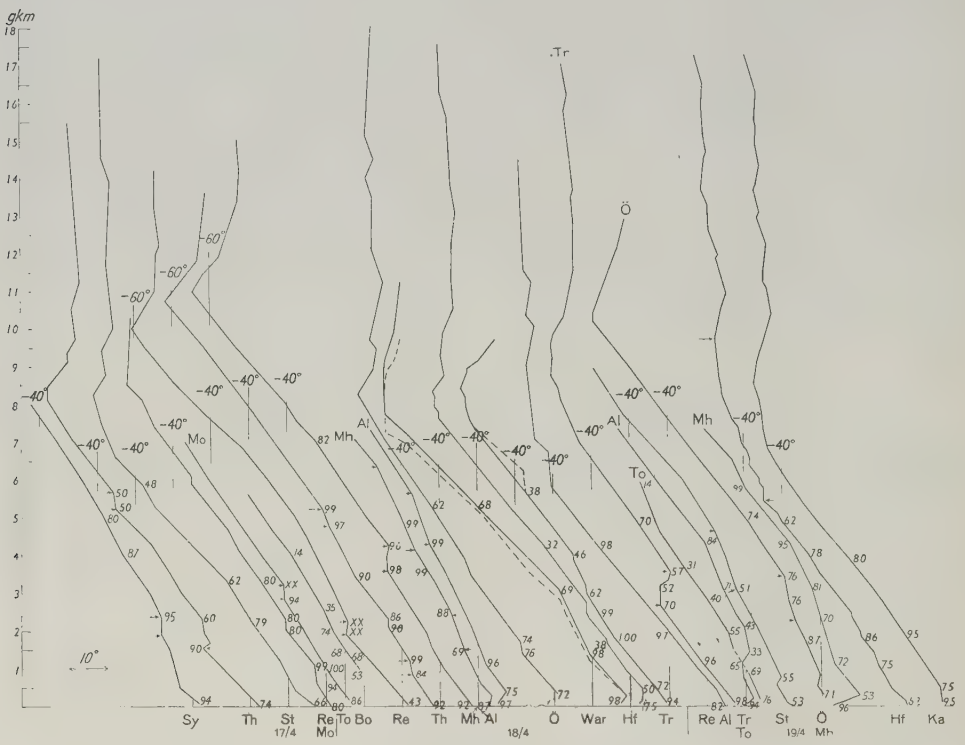



Fig. 18. Some ascents, April 17th.—19th. Syktyvkar, Thorshavn, Stockholm, Reykjavik, Moscow — Toulose, Bordeaux, Reykjavik, Torshavn, Mildenhall, Aldergrove, Östersund, Warsaw, Helsingfors, Tromsö — Reykjavik, Aldergrove, Tromsö, Toulose, Stockholm, Östersund, Mildenhall, Helsingfors, Kajana.

having —61° and Östersund —44° (difference 17°). The low-pressure area over the Norwegian Sea at 300 mb. has a corresponding warm and low stratosphere, in accordance with the correlation results obtained by, among others, Dines (1912 and 1919), Schedler (1921) and Palmén (1932) (see Fig. 15 d). The height of the tropopause is relatively indefinite over large areas, as the aeroplane soundings do not reach so high, and the German radio soundings not only have been made at a different time but appear to be unreliable. The tropopause appears to be low over Western Germany, even during the morning, and the inclination of the tropopause appears to be steepest within the actual

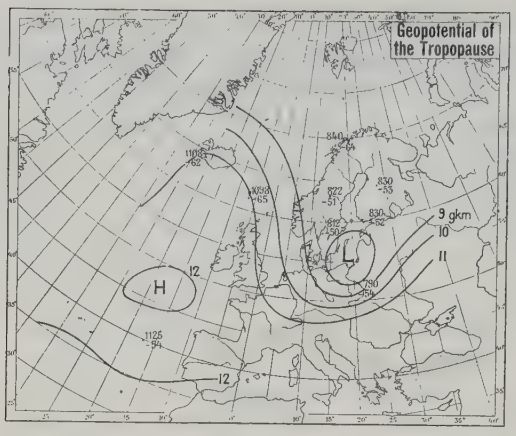
area where the wave disturbance occurs. On the 17th., at 2200 hrs. GMT, all the radio soundings have a corresponding low and indistinct tropopause. They were then made to the west of the disturbance. Cologne shows 7.8 gkm. and Erfurt 8.2 gkm.

**April 18th.**

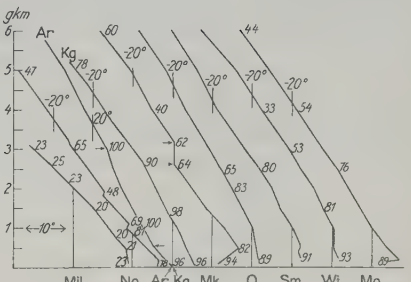
The depression over North Russia (Fig. 8) is being filled out. The sounding from Archangel (Fig. 19 f) indicates a frontal zone between 0.5 and 3 gkm. It is colder over Archangel than over Kajana, notwithstanding that Archangel lies within the precipitation region of the low-pressure area. If we try to find the trajectories we see that the precipitation is formed in air which doubtless has nothing in common with the warm-sector air from the earlier period of the cyclone. The upward gliding motion, or rather the elevation of the already fairly cold air inside the low-pressure area, causes precipitation. However, the aerological material is so scanty that it is best to refrain from an extensive discussion of the case and refer instead to the case of April 24th., when an old cyclone lay in a region where a more close net of aerological observations could be utilised in the analysis.

Before entering further into the discussion of the disturbance over Poland, and other problems, some time must be devoted to the examination of soundings from this day, and the corrections which have been introduced. After enquiries at the International Aerological Commission the author has obtained information that the characteristic point for Königsberg given in Deutsche Seewartes Bulletin should be 888 mb. and + 1.0° instead of 888 mb. and — 1.0°. The sounding at Warsaw (see Fig. 18), where the uncorrected sounding is dotted and the corrected one unbroken, gives over large intervals a superadiabatic gradient, and in addition the tropopause is abnormally low. In accordance with the account on p. 12 we have assumed a constant pressure error of 30 mb., and after correction the values from Warsaw show a fairly good agreement with those from other stations. It is possible that the correction is still somewhat too small. See the chart for 300 mb. (Fig. 19 c). Before correction the value in 300 mb. is 8 490 gm. and after correction 8 610 gm. To the temperature of Moscow has been added a positive correction of 3°, when the corrected geopotential for 300 mb. is 8 690 gm. as against the uncorrected value of 8 580 gm. Viazma, on the other hand, has appeared to be too warm compared with Orsha and Smolensk, and has been given a correction of — 1°.

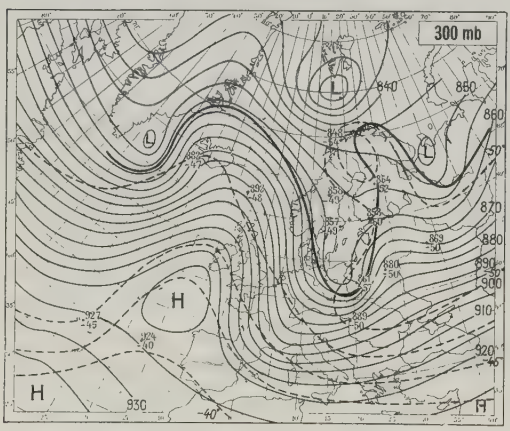
The wave disturbance over Germany of the 17th. has moved to the east, and a closed low-pressure area with its centre at approx. 1 007 mb. has formed over Poland. Ground observations indicate that a true occlusion process has occurred. A discontinuity in the temperature-height curve that may be interpreted as a warm-front can only be observed at Minsk at 2.6 to 3.2 gkm. (Fig. 19 f), but even there it is uncertain. The humidity is comparatively low and decreases from 64 to 62 and later to 60 % and lower. The humidity readings indicate that we are more probably concerned with the remains of a subsidence area which was very distinct over Germany on the previous day, or a faint newly formed one, which has subsisted or been formed inside the high-pressure ridge east of the low-pressure area. Even at temperatures of —10°, however, the humidity



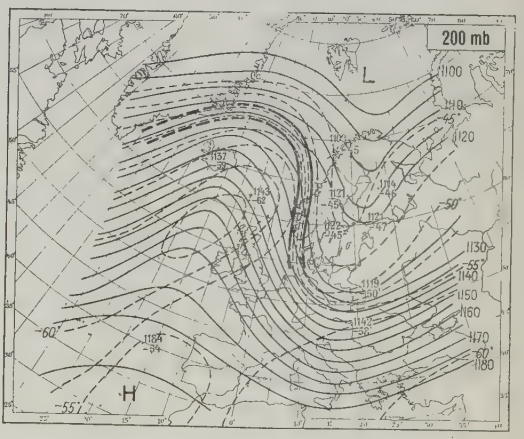

e) the tropopause.



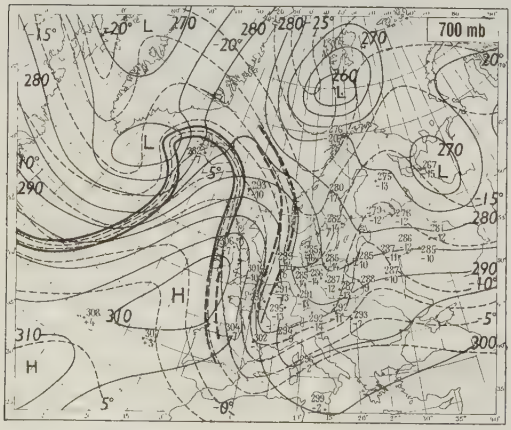

f) some temperature-height diagrams: Milan, Norderney, Archangel, Königsberg, Minsk, Orsha, Smolensk, Viazma and Moscow.



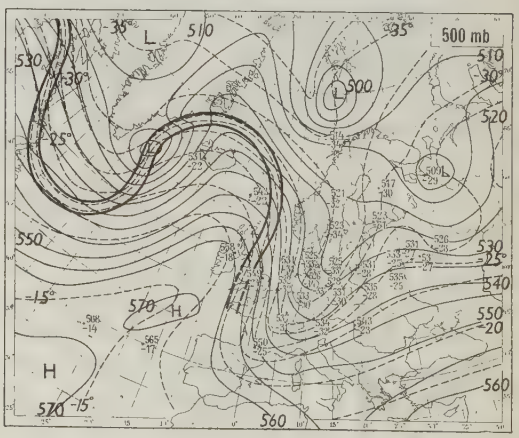

c) 300 mb.




d) 200 mb.




a) 700 mb.




b) 500 mb.

Fig 19. Geopotential charts for April 18th.

values are so uncertain, that there is a possibility that this actually is a warm-front. At the top of the layer the wet-bulb potential temperature is 7.0° or approximately the same as that at the top of the inversion layer in South Germany on April 17th. As has been previously mentioned, other soundings at Viazma, Smolensk and Moscow show no indication of a front. Even if the warm-front is diffuse, the occurrence of As-clouds and some rain in advance of the warm-front is distinct. Most of the rain, however, falls north and north-west of the centre. The cold-front is more distinct in the wind field as well as in the pressure field. The temperature and hydrometeors, at some places

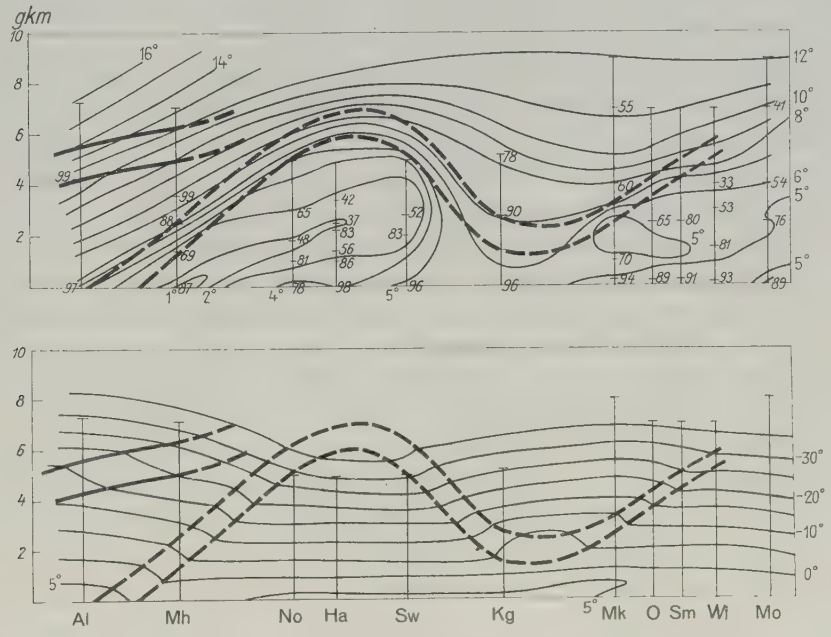



Fig. 20. Cross-section showing temperature (C) and wet-bulb potential temperature on April 18th. (Aldergrove, Mildenhall, Norderney, Hamburg, Swinemünde, Königsberg, Minsk, Smolensk, Wiazma, Moscow.)

even thunder, indicate the existence of a cold-front. It is certain that the rain at the warm-front is formed by upward gliding motion or general elevation and the amount of precipitation registered at, for instance, Warsaw, 5 mm. at 0700 hours GMT, shows that the elevation was quite considerable.

The lack of a front or frontal layer at Königsberg is especially remarkable. As in the study of the frontal wave of the 17th., the question arises how the formation of rain can be explained. On the basis of the ground chart one might possibly interpret the rain there as precipitation from air which during a rotatory movement has risen towards the low-pressure centre at a high level. However, the height-charts show that such a current of air cannot exist. Far below the 700 mb. level there is already a west to south-west air-current, the origin of which is quite separated from the warm-sector air.

A calculation of the horizontal advection-cooling effect in the Königsberg district shows that this is considerably larger at higher levels, such as 700 mb., than at ground level. In the manner employed by the author in drawing the height-charts (Fig. 19), which on the whole must be regarded as correct even if small adjustments are conceivable, advection-cooling is obtained at ground level of 0.15° per hour, at the 700 mb. level 0.25° per hour and at 500 mb. 0.25° per hour. Such cooling at high levels should cause labile stratification and precipitation in connection therewith. According to the ground observations (Fig. 8) the precipitation is partly rain from As-clouds or low bad-weather clouds like those at Rügenwalde 54.5° N, 16.3° E, Stolp 54.4° N, 17.0° E, and Poznan 52.3° N, 16.8° E, whereas at Danzig Ac-clouds were recorded simultaneously with As-clouds. At Deutsche Krone, 53.2° N, 16.3° E., »after showers» is reported. A west—east cross-section (Fig. 20) shows a warm centre at Königsberg at 1 to 2 gkm. which has been displaced eastward at higher levels. The wet-bulb potential temperature also shows that the stratification is moist-indifferent at 2.8 to 3.8 gkm. at Königsberg. At higher levels the stratification is stable and cloud reports made by the meteorological airman mention »Auflockerung». The cross-section shows, more effectively than height-charts, that a wind, the horizontal component of which in the vertical plane increases with the height, causes a considerable cooling in the district between Königsberg and Swinemünde. This cooling also increases with the height up to 4 gkm., above which it becomes almost constant. There is cause to point out here the difference of time between the soundings and the ground synoptical observations. As a rule the soundings were carried out 2 hours earlier in Germany than the ground observations at 0700 hours GMT, and in Russia they were 3 to 4 hours earlier. A sounding at Königsberg at 0700 hours GMT would no doubt have shown temperature values 0.5°—1.0° lower than those obtained from the sounding at 0500 hours GMT, whereas Minsk and other Russian stations in the section would have been warmer.

Attempts to find trajectories for the last 24 hours at the 500 mb. level bring us to Königsberg from the region south of Ireland (see Fig. 43 c, p. 103). The wet-bulb potential temperature of 8° at Königsberg agrees well with the corresponding value at the starting point of the trajectory, if we do not assume any vertical movement. Nor does elevation at the 500 mb. level seem probable, since »Auflockerung» occurs in the highest layers reached by the sounding at Königsberg. A possible elevation must, in the case of Königsberg, be limited to the lowest layers.

The present facts are not sufficient to determine whether the precipitation is partly instability-rain caused by a rapidly moving cold air current, or whether it is caused only by elevation. The quantity of precipitation, which is fairly large, indicates a considerable vertical movement, and this indicates that a general elevation has occurred. The existence of As-clouds and rain in the eastern parts of the low-pressure area, where the height-chart shows that no advective cooling at high levels is possible, is sufficient evidence for an elevation. On the other hand, the spreading of the rain area to the west, the advection-cooling there, and Königsberg's instability at the level of 2.8—3.8 gkm.,

indicate that rapidly moving cold air may also have played a considerable part in the forming of precipitation in the western parts of the disturbance.

The height-charts show how the cold air has penetrated far to the south over Germany. The front which lay over Scotland on the 17th. has practically disintegrated on account of the air having passed over the North Sea, the relatively warm water of which has rendered the air unstable and heated it to the same temperature as the preceding cold air.

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We find that the Alps form a barrier for the lowest cold air. This latter is obstructed by the *massif* and forces itself with storm strength round and down into the Rhône valley. A low-pressure area sheltered by the Alps is formed over North Italy. Cf. von Ficker (1920 B). At a greater height the current is less disturbed by the Alps, which causes a considerable cooling. While Rome at 700 mb. has a temperature of —2°, Milan, which has true Föhn-dry air, records —9° and Munich —14°. Over the northern parts of the Adriatic Sea we find gale with squalls and thunder and partly violent precipitation, which cause rapid cooling even at ground level. A wave of the cold-front is formed at ground level, but to start with this wave has an almost constant position, formed as it is by the orography. At Venice drizzle is recorded. Thus, to a certain extent, upward gliding hydrometeors occur here also, although thunder and the height current clearly show the cold air advection. Toulouse (Fig. 18) is cold up to the greatest altitude (5.6 gkm.). Cazaux, though slightly warmer, is still relatively cold and shows no distinct signs of a front. Bordeaux, without humidity readings, (Fig. 18) shows a zone at 1500 hours GMT almost with isothermy at 3.1—4.2 gkm. If we consider the high pressure over England, we find that the temperature at ground level is fairly low, and that the air cannot be regarded as tropical. This coldness is by no means mainly a consequence of night radiation. The ground inversion at Aldergrove and Mildenhall (Fig. 17) does not amount to more than a bare 2°. It is not until greater altitudes that warmer air has penetrated from the north-west. Unfortunately the English soundings give no or insufficient characteristic points, which makes it still more difficult to analyse them. Judging from the points given, which usually show the standard pressures, it is possible that there is a faint front at Mildenhall between 1.5 and 2.4 gkm. and a frontal zone between 4.1 and 6.2 gkm. (see the section, Fig. 20). At Aldergrove the gradient is considerably reduced between 4.3 and 5.6 gkm., which indicates a quite widespread frontal zone. If we study the vertical section or the sounding-curves for Mildenhall and Aldergrove, it is striking that the temperature difference is practically constant at all levels, and that the isotherms are consequently almost parallel equidistant lines. The warm-air advection which, according to height-charts and upper winds, comes from the north-west, is distinct, whereas the indications of fronts, where they exist, are diffuse. It is worth mentioning that the temperature at Bordeaux at 1500 hours GMT shows a distinct front or inversion. Nevertheless, if this front had been recorded according to the same method as the English soundings, i. e. only for standard pressures, it is not certain that it would have been possible to analyse the front from the sounding. It is, however, probable

that the possible previously formed front would have completely or partially disintegrated in the English high-pressure area, and in any case the fronts there must be decidedly less distinct than further to the north.

At Thorshavn the ground temperature has risen to +9°, which is higher than the temperature of sea-water. The current is south-westerly, and here it is undoubtedly a question of warm-air advection. A transition zone must exist at ground level between this advected warm-air mass and the air mass at the Norwegian coast, flowing from the north, the temperature of which is 3—4° at 64° N. A front cannot, however, be aerologically determined to the east of Thorshavn. At Thorshavn (Fig. 8) light rain falls from As-clouds, and the sounding (Fig. 18) shows a distinct warm-front between 3.6 and 4.2 gkm., with a high humidity. However, a general rise of pressure prevails within the region, and therefore typical pressure tendencies cannot be observed. At Reykjavik the ground temperature is +8° and light rain falls with a south-west wind. On North and East Iceland the temperature is 0° to 1°; this district has thus not been reached by the warm air. Whether Reykjavik at 0500 hours GMT, when the sounding was made, should be regarded as lying within the warm-sector, is uncertain (see Fig. 18). Possibly a faint front may be assumed to exist at 0.9—1.2 gkm. and an inversion at 2.1—2.3 gkm. The comparatively low lapse rate with a large degree of humidity which prevails between 3.4—5.2 gkm. gives us an idea of the complex nature of the disturbance. It must, however, suffice to state that it is not until this higher level that the temperature has reached tropical air values, which are only 5—6° lower than Carimaré's values at 40° N.

In order to discuss the development of the weather during the next 24 hours it is necessary to examine the temperature figures for Reykjavik. On p. 14 it has been pointed out that the temperature values at Reykjavik are probably too high compared with the values determined with the Väisälä-sonde (or the pressure values are too low, or there is a combination of temperature and pressure errors), but that a constant systematical error exists cannot be regarded as probable. In the present case it might be suspected that the temperature was too high or the pressure too low.

The temperature gradient, however, is moist-indifferent with the given values in the layer between the ground, where the temperature and humidity values are reliable, and the first characteristic point. Therefore we have no reason to expect the higher point to be too warm or to have too low a pressure, especially as the air is a warm mass flowing northward over a comparatively colder sea, and thus ought to be fairly stable. Whereas the values from the lower layers can thus be regarded as accurate, it seems probable that the temperature is too high or rather that the pressure is too low in the higher layers of the troposphere and in the stratosphere, and we can assume that the error from 0 mb. at the 700 mb. level increases to —20 mb. in the tropopause (cf. the discussion of the tropopause, p. 54). However, in the height-charts and sections no correction has been made, considering the uncertainty of such a procedure.

Reykjavik is situated considerably further to the north than Thorshavn and thus the section (Fig. 21) will not be a plane section. The front at Reykjavik at 4.7—5.2 gkm.

could thus correspond to the front at Thorshavn at 3.5—4.2 gkm., but in that case the ground front would run several hundred kilometres to the south of Reykjavik.

The values of the wet-bulb potential temperature up to the 500 mb. level at Reykjavik are considerably higher than the corresponding values at Thorshavn, in spite of the fact that the latter place lies further to the south. The rain which falls at Reykjavik is fairly

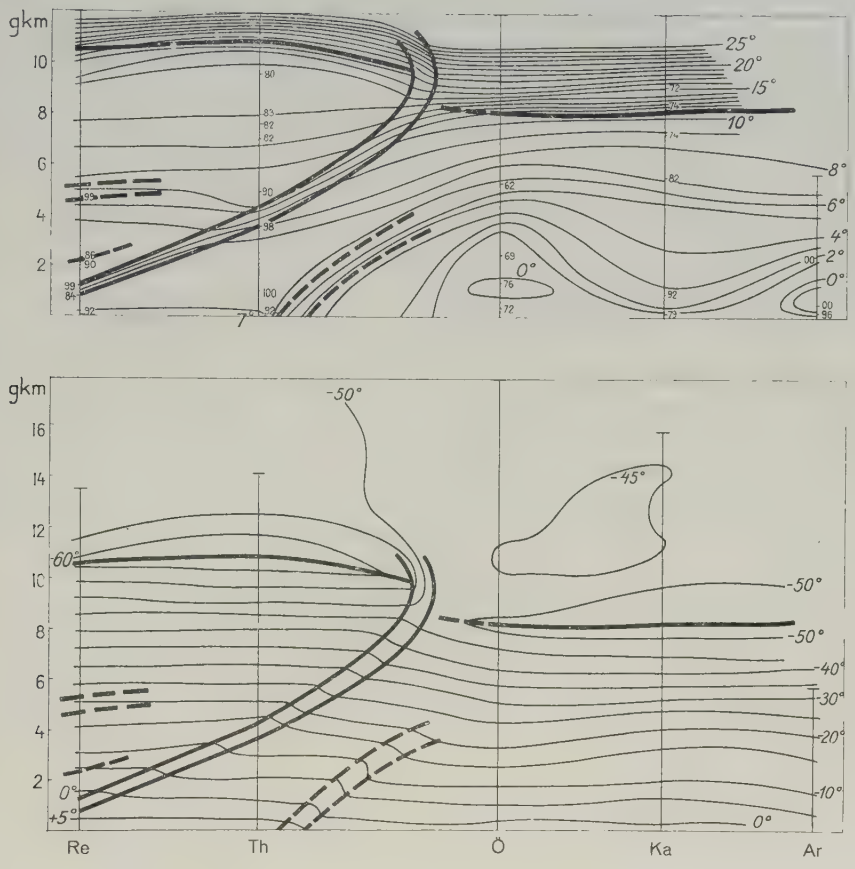



Fig. 21. Cross-sections showing temperature (C) and wet-bulb potential temperature on April 18th. 1939. Reykjavik, Thorshavn, Östersund, Kajana and Archangel.

strong and can hardly come from a level of over 5 km. We therefore assume that Reykjavik is quite near the warm-sector and we regard the front near the 500 mb. level as a secondary front of minor importance formed between the anticyclonic warm air mass, which has flowed round the high-pressure area north of the Azores, and sub-tropical air at a high level. The main front formed between the anticyclonic warm-air mass and a colder polar air mass to the north of it lies at 1 gkm. Finally we assume that another secondary front above Northern Iceland exists between the polar air mass and an arctic air mass

in the far north. In a real vertical plane-section the inclination of the main warm-front would be more normal and the front would have intersected the surface of the sea to the east of Reykjavik's meridian (and obviously at the same time south of it), in accordance with the ground chart.

At Tromsö an almost isothermal section is recorded between 5.6 and 6.2 gkm., which, according to H. Johanssen (1942), is a front or frontal zone between **P** and **T**. It is, however, difficult to imagine the formation of such a front. It is no doubt more likely that the point 6.2 gkm. is based on some observational error such as too high a temperature or too low a pressure. Otherwise it is impossible to accept a sounding which gives a lapse rate larger than the dry adiabatic one between 6.20 and 7.34 gkm.; the temperature falls 12.6° in 1 140 gm. If the point at 6.20 gkm. is discarded a more reasonable curve is obtained.

On this day the contrasts of temperature are considerable. At 700 mb. Reykjavik has —7°, whereas Östersund, which lies more to the south, has —17°, and at 500 mb. the corresponding figures are —22° and —32°. The difference at this level is still greater between Aldergrove (—18°) and Swinemünde (—33°).

The highest temperature difference at 700 mb. is 24° (Angra-Tromsö +4° and —20°), at 500 mb. 20° (Angra —14° and Tromsö —34°), at 300 mb. 14° (Carimaré —40° and Tromsö —54°) and at 200 mb. 17° (Thorshavn —62° and Tromsö —45°).

Palmén (1933) has recommended the use of the potential temperature at the tropopause as an aid to analysis. He has shown that in individual tropopause-surfaces the values of the potential temperature only vary to a small degree even if the height of the tropopause may vary considerably. In Table VI, p. 69, some values of the potential temperature at the tropopause level have been assembled. At Reykjavik the value on April 18th. is much higher (333°) than is customary at these latitudes. If we assume a pressure error of —20 mb. at the tropopause level and make a correction for it, the value 325° is obtained, which is characteristic of tropical air at Thorshavn, Östersund and Stockholm on the following days.

Even with this correction the tropopause is high over Reykjavik in spite of the northerly position of this station, where, even in tropical air, a certain fall of the tropopause is customary. The height of the tropopause indicates that Reykjavik is situated within, or in immediate proximity to, the warm-sector. Over the wave disturbance above Poland the tropopause is very low, although Warsaw has been corrected for a pressure error of 30 mb. Even if some uncertainty prevails regarding the sounding, the low tropopause must be a reality. Thus Stockholm has a lower tropopause than Östersund, which in its turn has a lower tropopause than Tromsö. At the same time temperature values of —50.0° at Stockholm, —51.3° at Östersund and —54.2° at Tromsö are observed. (See Fig. 19 e).

### April 19th.

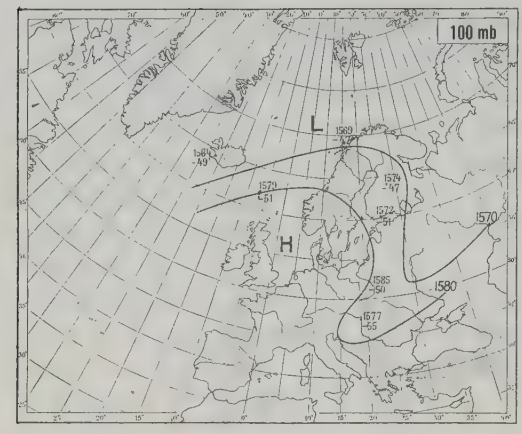
The aerological material from Russia for this day is less abundant than on the 18th., and the low-pressure area with its centre near Moscow (Fig. 9, p. 33) cannot be accurately

examined. It is true that the position of the cold-front at ground level is easy to determine, but the position of the warm-front is impossible to ascertain. In South-Eastern Russia the advective heating is considerable. At 700 mb. Sevastopol has $-1°$ and Rostov $-4°$ (see Fig. 22). Smolensk shows a faint inversion without any change of humidity at 2.0 -2.5 gkm. (Fig. 23). At the time of sounding at 0500 hours GMT Smolensk must have lain to the immediate west of the centre, and the inversion might be interpreted as the intersection with the front-surface at its most northerly part. The wet-bulb potential temperature, only 2.2°, is, however, also very low over the front compared with the case of the possible previous warm-front, where the value at Minsk on the 18th. was 7.5°. The trajectories (Fig. 43 a) indicate that the air at the 700 mb. level has come from the cold air region over South Sweden on the previous day, and the value of the wet-bulb potential temperature agrees with this. The humidity values at the prevailing low temperature, $-14°$, are also already so uncertain that the humidity-constancy at a high level in the sounding need not be regarded as real. Instead of the warm-front it may be the cold-front or a subsidence-inversion in the cold air. If the inversion is to be regarded as a warm-front, it is clearly a new formation since the 18th.

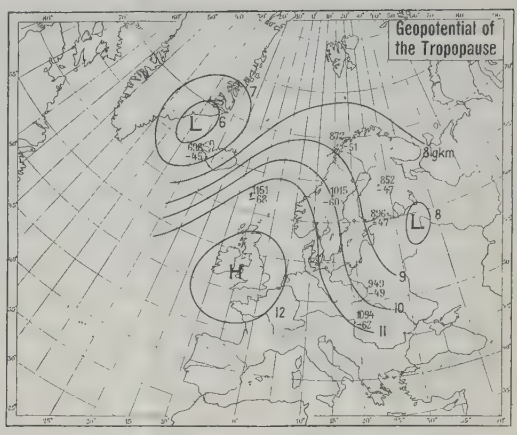
The precipitation at the centre of the low-pressure area is caused by an air mass which is considerably colder than that which formed the warm-sector on the previous day. The most important factor in the disturbance is the cold air, which pours in over South Russia at all levels from the west or north-west. The cold air which has its centre between Tallinn and Smolensk extends far to the south-west. While Tallinn at 700 mb. has $-17°$, Warsaw shows $-16°$, Munich $-14°$ and Toulouse $-11°$. The cold air has also forced itself over the Alps and caused a cooling of 5° at Rome. At the 500 mb. level cold air can also be observed far to the south; Toulouse (somewhat too cold?) shows $-26°$, and thus at 47.5° N is about 6° colder than Thorshavn at 62° N. As far out as Carimaré the cooling since April 18th. is distinct, although reduced to 3° at 700 mb. It is clear that this new cold air moving round the high-pressure area later on (April 21st.) appears as warm air at the cyclone which is then formed over Northern Scotland. At Angra, however, it is especially warm, $+5°$ at 700 mb., in the south-westerly current of air to the east of the low-pressure area at 37° N over the Atlantic.

The pressure rises over Southern Scandinavia, the British Isles and as far away as the Balkans. This rise of pressure is obviously great within the area where advection of cold air in the troposphere is great, and this advection must naturally contribute to the rise in pressure. However, the area of increase has a much larger extension and is considerable also in regions where the tropospherical advection causes a great rise in temperature. In the stratosphere, on the other hand, a cold advection prevails within the section of the area of increase which has a warm-air advection in the troposphere, but it is clear that advection effects alone cannot cause the existing changes of pressure.

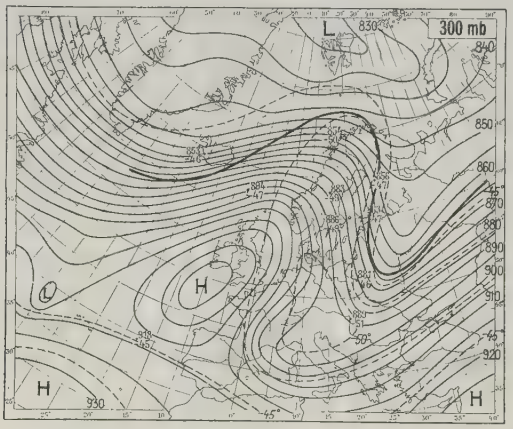
By studying the height-current with the aid of pilot-balloon observations, cloud measurements and geopotential charts for 500 mb., Scherhag (1933 and 1934) has found a connection between the streamline divergence at this level and the deepening of low-pressure areas. J. Bjerknes, P. Mildner, E. Palmén and L. Weickmann (1939) have shown that the



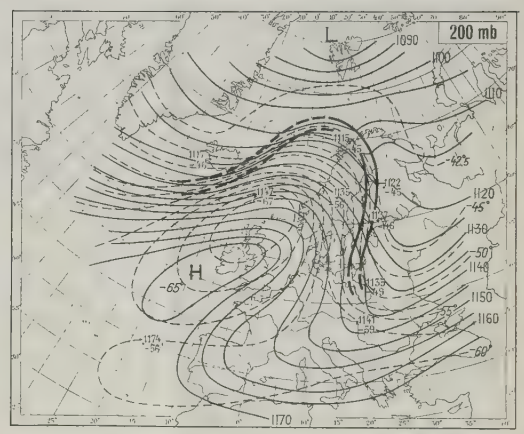

e) 100 mb.



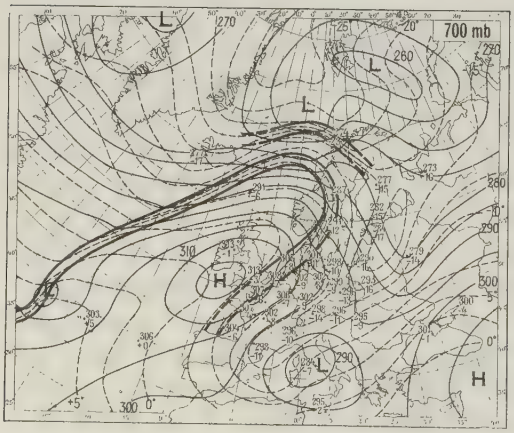

f) the tropopause.



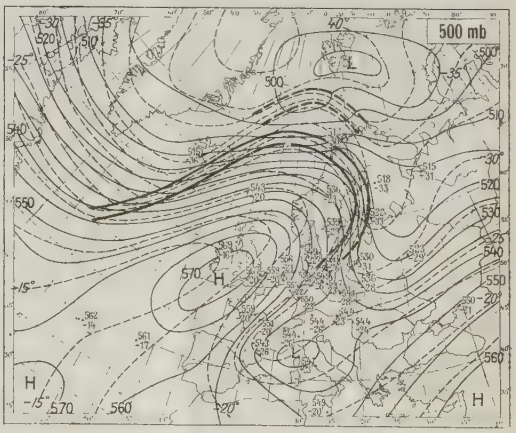

c) 300 mb.




d) 200 mb.




a) 700 mb.




b) 500 mb.

Fig. 22. Geopotential charts for April 19th, 1939.

validity of this empirically determined connection is limited to a short period in the existence of young cyclones. Through Scherhag's works attention has been called to other questions in this connection. J. Bjerknes has developed a theory regarding the movements of young extra-tropical cyclones. He starts from the considerations of V. Bjerknes and others (1933) regarding changes of pressure at ground level as caused by a wave in the polar front surface. The upper wave found by von Ficker (1920 A) connected with the frontal wave and originating from the tropopause region is of a secondary character. Assuming a gradient wind, J. Bjerknes (1937) explains the propagation of the upper wave partially as a consequence of a divergence-convergence effect in the horizontal wind-field $v_x$, $v_y$ lying above a certain height $h$ in the upper parts of the troposphere. In advance of the pressure troughs the pressure falls on account of the fact that air is drawn away by horizontal divergence in an anticyclonic current. In the rear of the pressure troughs the pressure rises owing to accumulation of air caused by horizontal convergence in a cyclonic current. The effects of convergence and divergence are equal when the wave is propagated without change. If deepening or filling out of the upper wave is to come about, vertical movements must occur so that in a deepening depression a descent prevails over the post-central parts of the ground low pressure. We recall in this connection that low pressure at a high level is formed later than at ground level, which was already shown by Douglas (1921) and Schedler (1921). In the strengthening of an anticyclone an upward motion prevails within it.

A deepening of a low-pressure area at ground level is explained by Bjerknes as a consequence of the divergence of cold air in lower layers, which counterbalances and exceeds the convergence prevailing in the upper troposphere and the lower stratosphere perpendicularly above it. Van Mieghem (1941 and 1942 A) has generalised this theory so that it is valid even if the deviation from the gradient wind caused by tangential acceleration is taken into consideration, and also if the horizontal density-gradient is considered. Van Mieghem assigns the divergence-convergence effect to the momentum $\varrho v_x$, $\varrho v_y$.

Let us compare the conditions in Central Europe with these theories. From the geopotential charts it is evident that a geostrophic streamline-divergence prevails at all levels. Humidity values and temperature values in the lower troposphere do not indicate any subsidence; on the contrary the temperature values are low, in spite of the fact that the air must be heated from below by convection currents during showers. The upper troposphere is cold and the tropopause is high. Thus Budapest has a high and cold tropopause and a cold stratosphere long before a stratospheric tropical air advection has been able to have any effect, and this is over a troposphere which is cold at all levels. If we accept this sounding at Budapest, which it is reasonable to do, as its values correspond well with the 100 mb. chart, there is reason to assume that a vertical upward motion has taken place in the 500—300 mb. level and that this motion is connected with a convergence at this and slightly lower levels. The true trajectories must differ considerably from the geostrophic streamlines which diverge, and we assume that this difference is connected with the retardation of the wind within the area in question.

In this connection we also wish to refer to another treatment of same problem, in conjunction with the cyclogenesis on April 22nd. (p. 90).

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The high-pressure over England is still cold in the lower layers. Not before the 2 gkm. level does Aldergrove show really warm air; at Mildenhall we find a frontal zone between 1 and 3 gkm (Fig. 18). Signs of fronts in the German soundings are small (see the diagram, Fig. 23, Norderney, Hamburg, Swinemünde) and the fall of temperature from Aldergrove to Warsaw is fairly continuous, although a certain accumulation of isotherms renders it justified to speak of a frontal zone. As mentioned above the frontolytical effect caused by subsidence in the high-pressure area is inconsiderable, and we must therefore assume that the front was already diffuse in this region at an earlier stage.

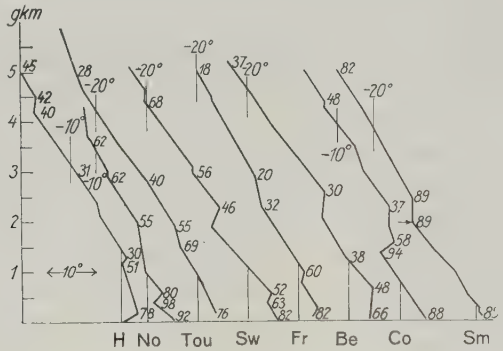



Fig. 23. Some temperature-height diagrams on April 19th. 1939. Hamburg, Norderney, Toulouse, Swinemünde, Frankfurt, Berlin, Cologne and Smolensk.

In the Heligoland Bight drizzle is recorded at some places, which is probably caused by cooling of a low layer of clouds by radiation. At Norderney the stratification between 100 m. and 450 m. is distinctly moist-labile. According to the reports of fliers in clear text there are Sc-clouds at Norderney. Schwerdtfeger (1943) assumes that the formation of Sc-clouds is connected with radiation cooling. It is improbable that, as has been indicated in certain bulletins, the above-mentioned drizzle could have any connection with the warm-front. The rain is formed in an Sc-bank of clouds with its upper level at 450 m., thus in an air mass which obviously lies below the remaining frontal zone.

Further to the north the warm-front is distinctly indicated in a sounding from Stockholm at 3.0—4.7 gkm. At Östersund (Fig. 18) the front is also very distinct, in full agreement with the experience that warm-fronts are best developed at high levels. Compare J. Bjerknes und E. Palmén (1934). The front at Östersund has a height extension of approx. 1 100 gm. (between 2.3 and 3.4 gkm.) and the horizontal change of temperature in the front is 4.5°, as at Stockholm. The front is identical with the one

which lay over Thorshavn on the previous day at approx. 4 gkm. The wet-bulb potential temperature at the upper level of the front is approx. 11° on both days and the trajectories also verify the identity (See Fig. 43 a). The absence of precipitation at Östersund, where there is to be found a bank of As-clouds, and the complete lack of clouds at Stockholm, indicate that the ascending motion at the front surface, which seems to be in-

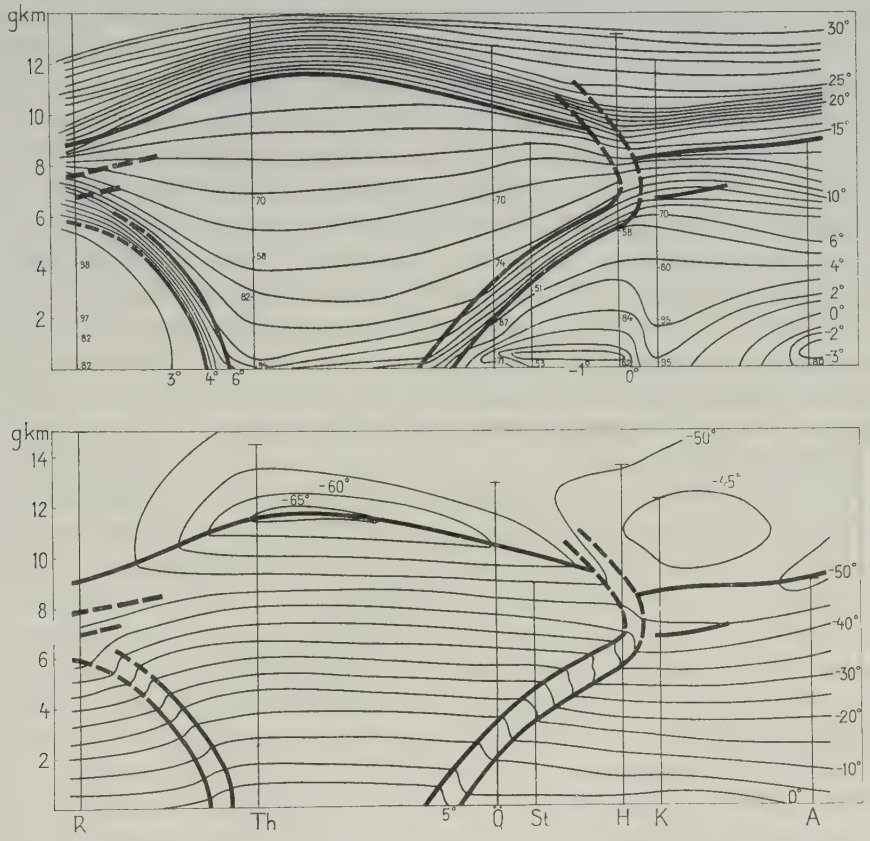



Fig. 24. Vertical sections showing the temperature and the wet-bulb potential temperature on April 19th. Reykjavik, Thorshavn, Östersund, Stockholm, Helsingfors, Kajana and Archangel.

tense near the centre of the low-pressure area, is relatively weak at Östersund at a height of 3 gkm., while at Stockholm at 5 gkm. it has changed into a weak descending motion. It is naturally only reasonable that the ascending motion near the centre of the cyclone is, at a certain distance from the centre, compensated by a downward motion not only in the northern cold regions, but also, to some small degree, in the more southerly and warmer districts.

It might be expected that, as the front-surface is so well defined at Östersund and

Stockholm, it could also be followed to Helsingfors and Kajana. With a normal slope of 1/100 or 1/150 the front at Helsingfors would be found at 6.5—5.4 gkm. and at Kajana somewhat higher up. In calculating these heights consideration has been taken of the distance between the stations, the difference of time between the observations and the velocity of the front along the connecting line between the respective stations.

At Helsingfors a discontinuity in the sounding occurs at 5.4 gkm., which might be interpreted as an indication of a front (see Fig. 18). The slope would amount to approx. 1/150. At Kajana it is more difficult to find any such indications, although the frontal distance at 700 mb. (Fig. 22) seems to be inconsiderable, or at least not greater than the distance from Helsingfors to the front. In the cross-section (Fig. 24) we see an interpretation of the front. The low temperature values in the stratosphere and the low tropopause show that the tropical air has not yet reached the stations at higher and lower levels. At Helsingfors the tropical air would have started to come in at 5.4—9.6 gkm., whereas its arrival at higher levels as well as at lower ones would occur later. The tropical air in the stratosphere would thus break through as a type of cold-front. A similar interpretation has previously been given in other cases (Bjerknes and Palmén 1938; Nyberg and Palmén, 1942). In connection with the cross-section the stratospherical frontal zone on the 200 mb. level has been drawn as if it were to the west of Helsingfors. Kajana can be assumed to lie in the immediate vicinity of the most easterly point of the frontal zone.

The conditions further to the north are shown in the sounding of Tromsö (see Fig. 18). Here we find an unusually sharp front at 2.6—3.6 gkm. As-clouds are reported; somewhat further to the south-west at Lofoten snow is recorded and further to the south rain. It is most natural to conclude that the front is a continuation towards the north of the warm-front of Östersund and Stockholm, and that the upward gliding motion here is considerable, and therefore causes precipitation. Below the warm-front at Tromsö the air has an arctic temperature, at 700 mb. —23°, and we see from the charts of the previous day how this air has pushed down in the rear of the low-pressure area which then lay over Björnön, and on the 19th. is to be found to the west of Novaya Zemlya. The front has grown stronger in the deformation field to the west of the low-pressure area, which explains its distinctness comparatively near the centre of this area.

On several occasions when aerological analyses have been made, the wet-bulb potential temperature has been observed to fall towards the north of the front surface, but the temperature fall has usually been fairly small; in Bjerknes and Palmén (1937) for instance, it is about 3° per 1 000 km. The difference of wet-bulb potential temperature between Mildenhall (approx. 12°) and Östersund (9.8°) is of approximately the same degree. Between Östersund and Tromsö, however, the wet-bulb potential temperature falls much more rapidly. The temperature at Tromsö is actually so low that the air mass can hardly be called **T**, and we do not regard the front at Tromsö as identical with the front further to the south.

We must, however, investigate whether the temperature and pressure values from Tromsö are accurate. For this purpose we have drawn a chart for the 100 mb. level

(Fig. 22 e) and with its aid we find that the value from Tromsö, 15 690 gm., is reasonable when compared with the values of Thorshavn, Kajana and Helsingfors and the extrapolated values from Reykjavik, Östersund and Stockholm. A constant temperature error of one degree corresponds to a geopotential error at 100 mb. of approx. 70 gm., and a pressure error of 10 mb. to a geopotential error of 40 gm. (according to Tab. IV p. 69). A temperature error is improbable on account of the fact that the temperature values at 100 mb., at which level the contrasts have largely been levelled out, are the same at Tromsö as at Kajana close by. If the temperature were still too low at Tromsö a correction would cause a rise in the geopotential at 100 mb. of 70 gm. per degree. The correction for 1.5° would cause the geopotential values of Thorshavn and Tromsö to become equal, and it would also mean that an opposed pressure gradient existed at higher levels. There is no reason to assume such a pressure distribution. If the recorded pressure were 25 mb. too low, the gradient at 100 mb., between the two stations would also disappear; thus 25 mb. is an error too large to be possible. The 25 mb. error corresponds to an error at the 700 mb. level of roughly 2°. This is the largest conceivable constant error, but the given values appear to be more reasonable.

In calculating the wet-bulb potential temperature at the top of the front, 3.8° is obtained from the given values. The humidity is given as 54 %, but as the temperature in the layer is about —20° this value is extremely unreliable. With regard to reported As-clouds we assume the humidity to be 100 %, which is probably too high as the cloud presumably consists of ice crystals. In this case the calculated value is 4.9°. If we were to assume a pressure error of 25 mb. this value is still not more than 6.4° which, although it exceeds the maximum value, is very low compared with the frontal value at Östersund which was 9.8°.

Thus we assume that the temperature values at Tromsö are more or less accurate, and that in accordance with the discussion of the 18th., the values from Reykjavik for the 18th. are accurate in the lower layers. If we try to find the origin of the trajectory which after 24 hours ends at the upper part of the frontal zone of the Tromsö sounding, we reach a point near Reykjavik (see Fig. 43 a). It is true that the calculation of the trajectory is uncertain considering the relatively rapid changes of pressure in the district. The trajectory runs, however, south of the low-pressure centre all the time and therefore the errors involved can hardly be more than 300 km. in length and 200 km. in breadth. The boundary regions are obtained if in separate calculations we consistently choose such extreme values of wind direction and wind force as interact. Then we observe that the starting point of the trajectory probably lies to the north of the main warm-front on the 18th. but possibly south of the secondary warm-front. To the south of the main warm-front the wet-bulb potential temperature even at ground level is as high as +7° and rises with the height, whereas the corresponding value at the upper level of the warm-front at Tromsö on the 19th. doubtless lies below 6.4°, and probably only amounts to 4.3°. It is possible that the warm air at Tromsö has been cooled by radiation. The absence of precipitation, which should have followed a cooling of this type, contradicts the possibility of any considerable radiation-cooling. It is quite out

of the question that such violent cooling has occurred on the trajectory to Tromsö, as to cause a fall in the wet-bulb potential temperature of more than 3° or approx. 5° C, while no cooling whatsoever has taken place on the trajectory to Östersund. According to theoretical calculations made by Möller (1943), the air at the upper cloud level can be cooled several degrees in 24 hours, but then moist-labile stratification takes place, and this is not the case at Tromsö. How great the cooling in this case may be is difficult to calculate. According to a previously quoted work by Möller (1935), the cooling of a whole air-mass by radiation cannot amount to more than approx. 1° per 24 hours.

From the above discussion we draw the conclusion that the front at Tromsö is not identical with the front at Östersund and further to the south. On the 18th. the ground chart indicated the existence of two warm-fronts, of which only the more southerly one could be verified by aerological observations. In a similar manner the height-analysis on the 19th. indicates that two warm-fronts exist, whereas the ground-analysis does not indicate a warm-front with certainty, and in any case it hardly renders the more southerly front visible with the desired clarity. Even if the southerly front has partly dispersed in its northern section which is parallel with the current, there remains in this district a large baroclinicity in the upper troposphere.

The aerological material does not permit a corresponding analysis of the cold-front. According to ground observations a cold-front runs immediately west of Thorshavn. At this place there are at high levels no indications of horizontal advective cooling, which otherwise is customary long before the cold-front at ground level. See Van Mieghem (1937, 1939 A and 1939 B) and Nyberg and Palmén (1942). Nor is a lowering of the tropopause or heating in the stratosphere observed, which is still more remarkable. This appears to be connected with the fact that the change of wind at the front is inconsiderable and that the air after the front only changes character slowly. At Reykjavik (Fig. 18) the air is cold; at 6.6—6.7 gkm. isothermy prevails, which can be interpreted either as a cold-front or as a newly formed low tropopause. The fall which has occurred in the tropopause is distinct, cf. the cross-section Fig. 24. At Tromsö the tropopause is high and cold. It is true that the potential temperature 318° is lower than at Östersund where it is 324°, but such a fall in the potential temperature as 6° in 700 km. within the same air mass can be taken as reasonable, and therefore the air in the tropopause region at Tromsö may be regarded as **T** even if a distinct front between **P** and **T** cannot be observed at Tromsö in the upper part of the troposphere.

Let us attempt to determine the trajectory for the air over Tromsö on the 19th. at the 300 mb. level, which can be done with greater accuracy than at the 700 mb. level (see Fig. 43 d, p. 103). If we calculate the starting point of the trajectory we reach a point at 62° N, 29° W, or slightly south-west of Reykjavik. At lower levels and even at higher ones the corresponding points must lie further to the north-east, since the wind force at 300 mb. is in this case higher than at other levels. At 300 mb. the air at Tromsö more or less corresponds to that at Reykjavik on the 18th., at lower levels to air from a more north-easterly and considerably colder place and at higher levels to air also coming from a more north-easterly but considerably warmer locality than Reykjavik. The

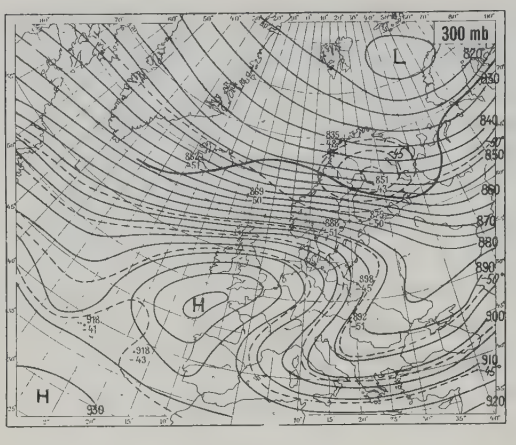
fact that the real trajectories are not horizontal means that the trajectories calculated at a certain level are somewhat incorrect. However, considering the relatively small change of wind, in direction as well as strength, with height, and considering the relatively small changes of height, the errors cannot be large. Indeed compared with the chance errors which are due to uncertainty in the drawing of isobars they may be disregarded. In a comparison between the temperatures of Tromsö and Reykjavik it seems most remarkable that the high tropopause found at Reykjavik has completely vanished. The troposphere at Tromsö is considerably colder, partly on account of advection of different and colder air than that at Reykjavik, but also partly on account of an ascending motion of air in the troposphere in connection with the deepening of the depression. In the stratosphere we observe a considerable rise of temperature, which is mainly attributed to a descending motion. Let us assume that these trajectories, at the 300 mb. as well as at the 250 mb. level over Tromsö, originate from Reykjavik on the previous day. Then we find a descending motion which is greater than the real one, as the true trajectory came from a more northerly, and, in the stratosphere, warmer district than Reykjavik. However, this deviation is probably not large. At the most the vertical motion amounts to 1 600 m. in 24 hours or practically 2 cm. per second. In this case the influence of advection on the temperature change appears to be larger than that of the vertical motion in the troposphere, whereas in the stratosphere vertical motions dominate.

To the west of the Azores there is a south-westerly current of exceptionally warm air. At 700 mb. Angra shows +5°, which is the highest temperature of the month. The distinct indications of fronts in the ground observations cannot be verified on account of the lack of aerological material. The height-charts, however, show that the depression extends to the 500 mb. level. The cold air of the low-pressure area is everywhere even warmer than the warm air at Thorshavn.

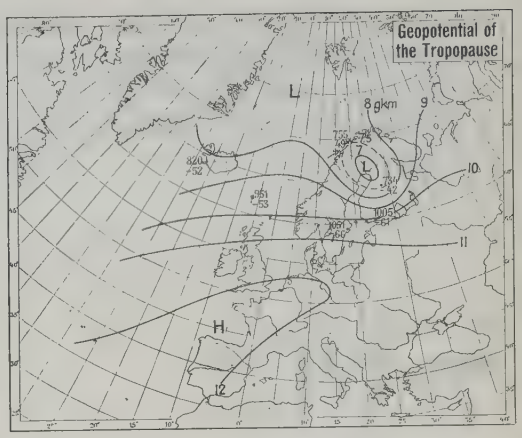
**April 20th.**

To the east of the Sea of Azov lies the centre of a closed low-pressure area (Fig. 10, p. 34). It extends only to a low altitude. Through the low-pressure area a cold-front runs in a north-easterly direction towards a low-pressure trough at 50° N—50° E. As-clouds occur and some rain falls on both sides of the front, which in sections is fairly sharp. The southern air current to the east of the front is warm and moist. In higher layers of air there is, as far as one can see, no warm air advection — on the contrary there is a faint cold air advection — and the precipitation can be explained as a consequence of labilisation from below through a slow and uniform heating of the layer at ground level simultaneously as the higher layers of air are being cooled, but other explanations are also possible.

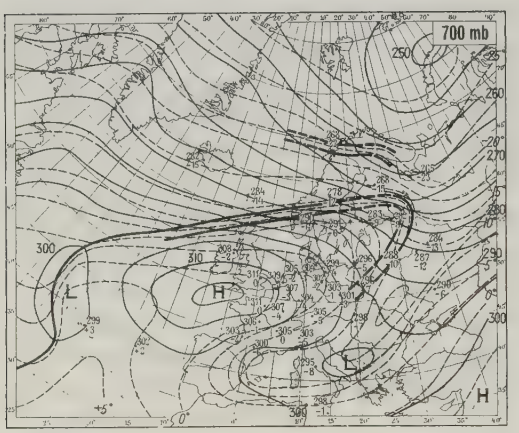
In the cold air up to 1.5 gkm., Kharkov (Fig. 26) has a temperature gradient greater than the moist adiabatic one, although the humidity values and cloud observations indicate that the air is not saturated. The cold-front lies between 1.5 and 2.5 gkm. In the rain district to the west of the ground cold-front, Balachev, 51° 33′ N 43° 09′ E, has an



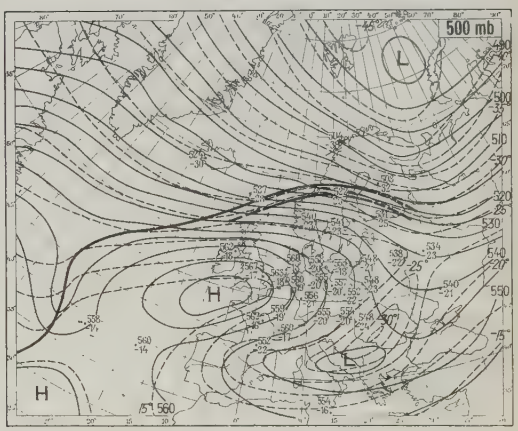

c) 300 mb.




d) the tropopause.




a) 700 mb.




b) 500 mb.

Fig. 25. Geopotential charts for April 20th. 1939.

east-north-easterly wind. There it can hardly be a question of elevation of warm air by an irruption of cold air at ground level, but of course we can assume that a general elevation takes place in the low-pressure area and the low-pressure trough, which would cause or at least contribute to precipitation.

The low-pressure area over Italy remains. It is very cold (Fig. 25) (at 700 mb. Rome has —8° in contrast to —5° at Milan and —1° on Malta), but it seems that it is being filled out and that warm anticyclonic air pours in from the north. The cold air over Italy is connected with the cold air lying further to the north-east. As the west-east current, on account of the prevailing pressure distribution, has become much stronger in the district between 50° and 60° N than further to the south, a cold air centre begins to appear to the east or north-east of Budapest. At the 700 mb. level it is probable that an isolation

of the cold air has already been caused by an advance of warm air, and at 500 mb. the isolation is undeniable. The continued existence of the cold air that has been cut off can be followed during the next day, as the wind force in the region is small and the movement is so slow that the air does not disappear from the area of the chart. In an earlier work by J. Bjerknes and H. Solberg (1922), the term »seclusion» was introduced to indicate the cutting off of warm air which occurred in connection with the occlusion process, when this was disturbed by orographic obstacles such as the mountains in Western Norway. This process, which appears to be fairly unusual, has certain characteristics in common with the one described above, which, however, is considerably more frequent. A similar case to that described here occurs during the next week in April.

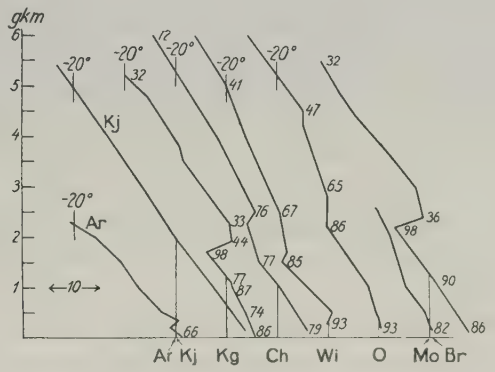



Fig. 26. Some temperature-height diagrams on April 20th. Archangel, Kjeller, Königsberg, Kharkov, Viazma, Orsha, Moscow and Breslau.

We call the process »cold-air seclusion», as distinct from the previously described seclusion, which only referred to warm air.

The warm-front which on the 19th. could still be observed over Mildenhall has completely vanished on the 20th., except at Slutsk, where it can be observed at 0.4—2.0 gkm. (Fig. 27 p. 67). Further to the south inversions are to be found at Königsberg and Breslau (Fig. 26) and possibly also Warsaw (Fig. 27) where the given point 748 mb. —8.0° is assumed to be 748 mb. —3.0°. These inversions are connected with a strong decrease of humidity, and the values of the wet-bulb potential temperature at the upper level of the inversion are remarkably low, at Königsberg 7.7°, Breslau 7.6° and Warsaw, corrected, 8.5° as compared with approx. 10° on the previous day at the upper level of the warm-front. It is doubtful whether these inversions have any connection with the warm-front. It is more probable that they are subsidence inversions, formed inside the high-pressure area in the air mass nearest ground level, which have never reached the high values of the wet-bulb potential temperature shown by warm air at higher levels.

The ground chart shows no apparent difficulties in the analysis. The warm-front and an occlusion front indicated in ground observations are preceded by As-clouds

and general rain or sleet in the south and snow in the north. This indicates an upward gliding motion. The surface temperatures after the warm-front and the occlusion front are as a rule 4° to 5° higher than those before the fronts. Such an analysis, which agrees well with the most recent ground observations, is not in concordance with the analyses of previous days. The secondary or more northerly warm-front cannot be retraced. It is possible that by occlusion it has been united with the cold-front, but in that case we must point out that the occlusion front has taken its place surprisingly well in the cyclone-pattern. This phenomenon is too remarkable to be regarded as a mere chance. Instead we assume that the occlusion front here actually has no connection with the previous fronts, which, as will be shown below, may with good reason be assumed to have disintegrated. Thus the occlusion front is a phenomenon caused by pressure distribution, change of pressure, and vertical air movements. Only in this way can the regular course of the occlusion front at the ground be explained, although the air masses which limit the front near the occlusion point have completely different origins and characters from the air masses limiting the front further to the north nearer the centre of the cyclone.

The main cold-front is rather diffuse and its exact position cannot be determined, but in the main it must run as the ground chart (Fig. 10 p. 34) indicates. Over South-Western Norway, the Shetland Isles and the extreme north of Scotland As-clouds and rain are observed. In addition, the pressure falls north as well as south of the front. We have reasons to interpret this as a symptom of a wave disturbance in its earlier stages. To the south of the front showers are reported from several places simultaneously with As- and Cb-clouds. Thus it is not a typical young warm-sector, but precipitation can hardly have been formed otherwise than by elevation of the air, in connection with which a fall of pressure occurs. The position of the front over the Atlantic can be seen with satisfactory distinctness.

To the north of the main cold-front, roughly parallel with it, a front runs from the centre of the low-pressure area. From a ground-synoptical point of view this front might be regarded as a back-bent occlusion. This type of front was first described by J. Bjerknes and H. Solberg (1922). Sometimes it occurs as a pure cold-front (J. Bjerknes, 1935) and sometimes, as has been described by Palmén (1936), as a dynamic front without thermal significance, formed perpendicularly under the deepest part of the upper wave. In the case treated here, the occlusion front is of a distinct cold-front character and causes at ground level a cooling of 5°—8°. Also further to the west over Iceland the front is fairly distinct, although the supply of cold air is now slower and the rise of pressure, which is greatest to the south of the front, indicates that the front there will rapidly decrease in sharpness.

To a certain extent aerological ascents verify the ground analysis, but sometimes it is impossible to achieve agreement between aerological data and the results which might be expected after a ground analysis. Helsingfors (Fig. 27), which lies completely inside the warm-air region, has, in complete agreement with this, a warm troposphere and a high and cold stratosphere. The same is the case at Stockholm. Slutsk (Fig. 27)

intersects the warmfront at 0.4—2.8 gkm. and is warm above it, but does not reach the tropopause, as the maximum height of the sounding is only 4.0 gkm. The air in the warm-sector at 700 mb. is a few degrees colder than on the previous day. The wet-bulb potential temperature at Stockholm is 8.6°, compared with 10° at Thorshavn, in the vicinity of which the trajectory started on the 19th. (Fig. 43 a). This cooling can be explained by assuming an elevation of the air, so that the air on the 19th. at 740—730 mb., where the potential wet-bulb temperature at Thorshavn was 8.5°, corresponds to that

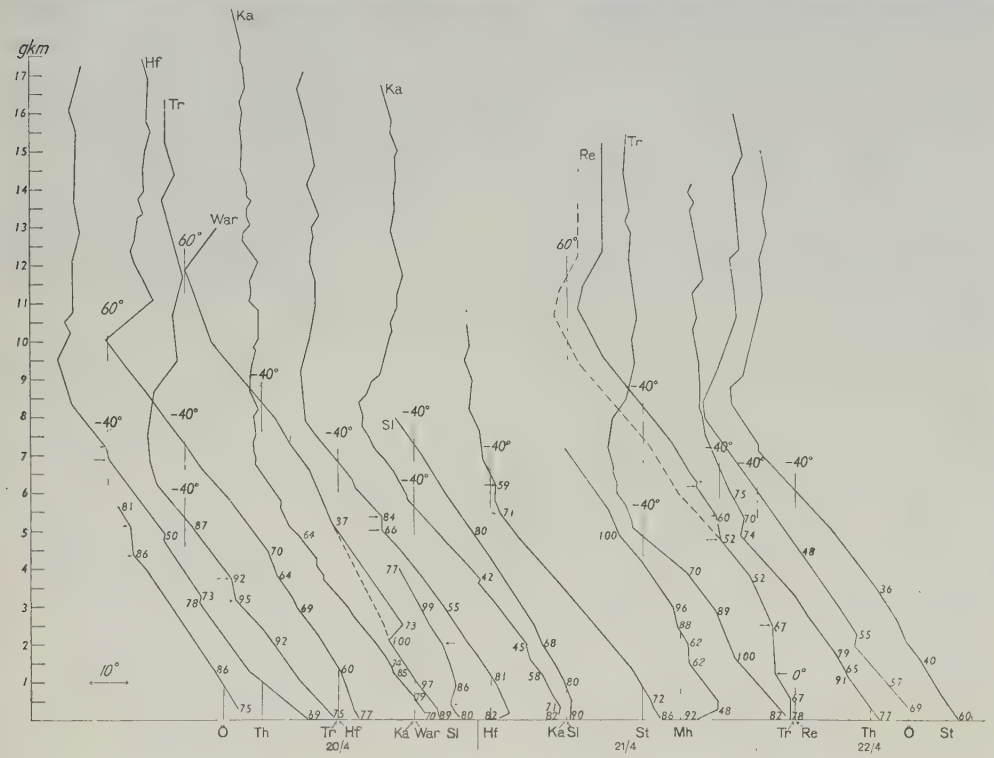



Fig. 27. Some ascents, April 20th.—22nd. 1939. Östersund, Thorshavn, Tromsö, Helsingfors, Kajana, Warsaw, Slutsk — Helsingfors, Kajana, Slutsk, Stockholm, Mildenhall — Tromsö, Reykjavik, Thorshavn, Östersund, Stockholm.

at 700 mb. on the 20th. The elevation of the air by approx. 300 gm. would increase the relative humidity from 80 % to about 100 %, and some water might possibly be precipitated, although the amount would be insignificant. The observations also show a considerable increase of cloud in the northern part of the warm-sector where, as at Stockholm and Helsingfors, 7—10/10ths. of the sky is covered with As- and Ac-clouds at the 700 mb. level without any precipitation occurring. The sounding of Östersund (Fig. 27) runs through the main cold-front at 4.4—5.1 gkm., and the front is fairly distinct at this level. The wet-bulb potential temperature at the upper level of the front is 9,7°, which is in complete accordance with previous limiting values for tropical

air at this latitude, e. g. at the warm-front at Östersund on the previous day. The maximum height of the sounding is only 5.7 gkm., but the course of the temperature compared with Stockholm indicates that the tropopause is relatively high and cold. On the basis of the observations of April 1939 at Tromsö and Thorshavn, Björkdal (1940) has produced a regression equation for calculating the height of the tropopause, with the temperature at 5 gkm. as a starting point. From this equation the value 9.3 gkm. is obtained for the geopotential of the tropopause at Östersund. The sounding of Kajana (Fig. 27) is more difficult to fit into the cyclone model. It shows no indication of a front whatsoever — the irregularities are of no significance — although the cold-front at ground level cannot be further away than, at the most, 300 km. to the south, and a cold-front with a normal slope of 1/50 to 1/100 would be seen at 6—3 gkm. The tropopause is low and the stratosphere warm, and the potential temperature in the tropopause is only 303° (cf. Tab. VI). This shows that the air in the upper troposphere and the stratosphere at Kajana has quite another origin than that of Helsingfors. The trajectory to Kajana at 300 mb. (Fig. 43 d, p. 103) seems to have started only slightly south-east of Reykjavik on the previous day. On a basis of the temperature at Reykjavik and dry adiabatic heating we find a downward motion during the day and night of 300 gm.

At Archangel, whose sounding unluckily only extends to 2.3 gkm., the air is very cold. The stratification is indifferent and has no front. Precipitation is said to be moderate. Considering the low temperature prevailing above the 700 mb. level and the small absolute humidity conditioned thereby, there are reasons to suppose that snow is formed below the 700 mb. level. Precipitation is thus formed in the northern parts of the depression, either by an overrunning of cold air at a high level, which labilises the air, or by general elevation of the air in advance of the ground occlusion-front. Judging from the height-chart, such instability caused by cold air is possible, as no cooling by advection occurs at ground level, but as a rule a certain amount of heating, whereas at high levels a cooling may be possible. On the other hand the precipitation further to south is undoubtedly connected with an upward gliding motion or elevation, and this fact goes to show that further to the north the precipitation may be explained in a similar manner, since the cloud system as well as the precipitation area is uniform and continuous. The upward moving air in the north is obviously so much colder than the air in the warm-sector that there must be two completely different air masses. It is possible that in the centre of the depression the air is somewhat warmer than further to the east and west, but in spite of this we must regard the upward moving air to the north of the occlusion point as a polar air mass gradually growing colder, finally even to become arctic air. Up to very high levels the air is strongly baroclinic, and at 700 mb. the temperature falls from —8° at Slutsk to —23° at Archangel, 700 km. distant. Elevation occurs, however, independently of the absolute temperature of the air and the origin of the air masses, and also, judging from aerological data, independently of fronts. It is doubtful whether air behind the occlusion front, which at ground level has the character of a warm-front, causes cooling aloft. If this were the case the elevation could be explained as a consequence of the cold air pushing in under the warmer air. This is, however, contradicted

*Table VI.*

**The values of the potential temperature $\Theta$ in the tropopauses, the heights of which are given in gkm.**

| | 17 | | 18 | | 19 | | 20 | | 21 | | 22 | | 23 | | 24 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\Theta$ | gkm | $\Theta$ | gkm | $\Theta$ | gkm | $\Theta$ | gkm | $\Theta$ | gkm | $\Theta$ | gkm | $\Theta$ | gkm | $\Theta$ | gkm |
| *Tromsö* | 303 | 8.2 | 300 | 7.6 | 316 | 8.4 | 291 | 6.2 | 292 | 6.7 | 283 | 5.1 | 292 | 6.3 | 303 | 8.2 |
| | — | — | 304 | 7.9 | **318** | 8.7 | 297 | 6.8 | 294 | 6.8 | 289 | 6.0 | 300 | 7.0 | — | — |
| | — | — | 309 | 8.4 | — | — | 306 | 7.6 | 304 | 7.6 | 295 | 6.6 | 308 | 7.7 | — | — |
| | — | — | — | — | — | — | — | — | — | — | 302 | 7.2 | — | — | — | — |
| *Reykjavik* | 311 | 8.5 | **324** | 10.6[1] | 293 | 5.8 | 301 | 6.4 | — | — | **324** | 10.7[1] | 297 | 5.7 | 303 | 7.1 |
| | — | — | 332 | 10.7 | 291 | — | 308 | 8.2 | — | — | 334 | 10.9 | 331 | 9.2 | 308 | 7.6 |
| | — | — | — | — | 302 | 7.0 | — | — | — | — | — | — | — | — | — | — |
| | — | — | — | — | **328** | 9.0 | — | — | — | — | — | — | — | — | — | — |
| *Thorshavn* | 307 | 8.1 | 325 | 11.0 | **328** | 11.5 | **324** | 9.5 | 305 | 7.9 | 311 | 7.6 | 317 | 9.3 | 315 | 8.9 |
| | 312 | 8.5 | — | — | — | — | — | — | 316 | 9.0 | 319 | 8.3 | **322** | 9.6 | — | — |
| | — | — | — | — | — | — | — | — | — | — | 346 | 10.3 | — | — | — | — |
| *Östersund* | 308 | 7.8 | 309 | 8.2 | 322 | 10.1 | — | — | 297 | 7.1 | 304 | 8.0 | — | — | 310 | 8.0 |
| | — | — | — | — | **325** | 10.3 | — | — | — | — | 309 | 8.4 | — | — | 327 | 8.8 |
| *Stockholm* | 297 | 6.6 | 310 | 8.1 | — | — | **318** | 10.5 | 292 | 5.4 | 309 | 8.9 | — | — | 294 | 6.7 |
| | 311 | 8.2 | — | — | — | — | — | — | 295 | 5.8 | 318 | 9.3 | — | — | — | — |
| | — | — | — | — | — | — | — | — | 318 | 8.2 | — | — | — | — | — | — |
| *Kajana* | 313 | 8.7 | 309 | 8.3 | 300 | 6.8 | 303 | 6.7 | 301 | 7.7 | 299 | 7.2 | 307 | 8.8 | 299 | 6.6 |
| | — | — | 322 | 9.1 | 306 | 7.2 | 311 | 7.3 | 309 | 8.4 | 307 | 8.1 | 311 | 8.8 | 305 | 7.6 |
| | — | — | — | — | 309 | 7.6 | 317 | 7.8 | — | — | — | — | — | 8.9 | 308 | 7.8 |
| | — | — | — | — | 315 | 8.1 | 328 | 8.7 | — | — | — | — | — | — | — | — |
| *Helsingfors* | 312 | 8.2 | 302 | 7.6 | 293 | 5.4 | **320** | 10.1 | 308 | 7.9 | 309 | 8.6 | 319 | 9.8 | 295 | 6.4 |
| | 313 | 8.4 | 305 | 7.9 | 300 | 6.3 | — | — | **325** | 9.2 | — | — | — | — | 298 | 6.7 |
| | — | — | 310 | 8.3 | 305 | 6.9 | — | — | — | — | — | — | — | — | — | — |
| | — | — | — | — | 335 | 9.7 | — | — | — | — | — | — | — | — | — | — |
| *Warsaw* | 319 | 10.0 | 298 | 7.7[1] | 328 | 9.6 | 345 | 11.9 | — | — | 315 | 9.7 | — | — | 322 | 9.5 |
| | — | — | 308 | 8.4[1] | 364 | 12.0 | — | — | — | — | 318 | 9.9 | — | — | — | — |

[1] Corrected values. — The thick figures show values typical for tropical air.

by the facts that the air has a stable stratification at Kajana and that no snow squalls or showers are recorded within the area behind the occlusion front. The extent of the snowfall is no doubt caused by several circumstances, but it would seem that its existence, i. e. the elevation, was in the first place connected with the low-pressure area and the fall of pressure.

A front, which at ground level is very sharp, runs westward from the low-pressure centre. In the sounding of Tromsö (Fig. 27) it is also distinctly indicated at 3.2—3.7 gkm. On the 19th. we found two warm-fronts at high levels, of which only the more southerly one could be retraced within a small area at Slutsk on the 20th. On the other hand, we find on the 20th. two distinct cold-fronts, of which the more southerly is almost certainly connected with the southern warm-front, i. e. the main warm-front of the previous day (see Östersund 4.4—5.2 gkm. Figg. 27 and 28). It is more uncertain whether

any connection exists between the northern warm-front of the first and the northern cold-front of the second day. The wet-bulb potential temperature on the 20th. is 0° at the cold-front compared with +3.8° on the 19th. at the warm-front. It is more probable that the cold-front of the 20th. is identical with the arctic front of the 19th., which then might also be regarded as a back-bent occlusion.

Thorshavn (Fig. 27) shows a small number of discontinuities, but all of them are in-

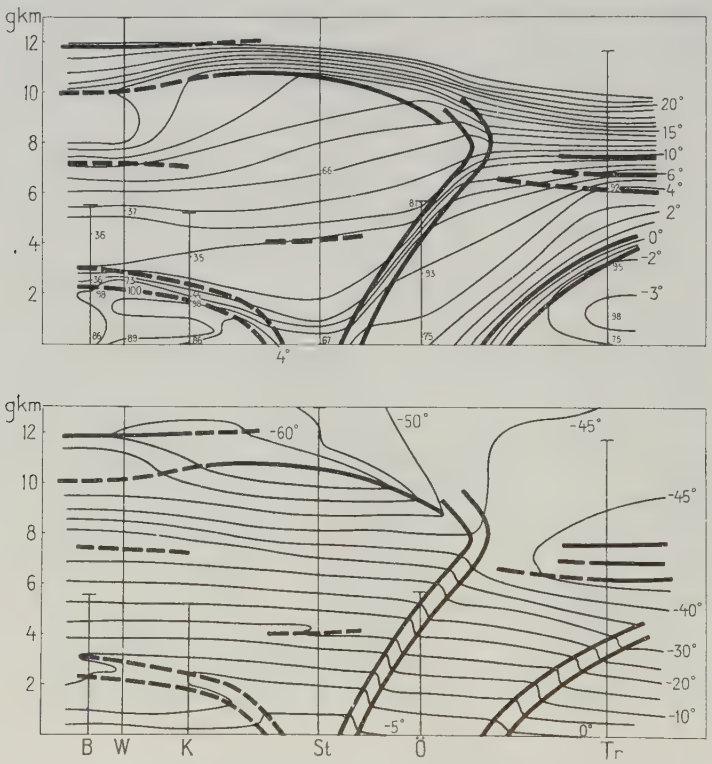



Fig. 28. Vertical sections showing the temperature (C) and the wet-bulb potential temperature on April 20th. Breslau, Warsaw, Königsberg, Stockholm, Östersund and Tromsö.

significant, the largest deviation from the normal temperature gradient occurring at 6.9—7.2 gkm., corresponding to an increase in temperature of only 2° to 3°. This might well be the cold-front. At 7.2 gkm. the wet-bulb potential temperature is approx. 11.1°, which roughly corresponds to the value of Östersund, 9.2°. The air at higher levels over Thorshavn has a moderately high tropopause and a stratosphere of an intermediate type between these of the anticyclone and the cyclone. Compared with Kajana, which lies at approximately the same distance from the cold-front as from Thorshavn, the

latter place has a high tropopause and a cold stratosphere. In the tropopause chart (Fig. 25) the depression of the tropopause in the region south-west of the low pressure over Northern Finland can be seen very distinctly. The tropopause topography shows how the tropopause has been sucked down south-east of Tromsö as if in a funnel. It also shows, just as in a number of previous investigations by Palmén and others, for instance Bjerknes and Palmén (1937), that the isohyps form closed rings around a minimum south-west of the cyclone centre. Thus, as Palmén (1933) first observed, contrary to earlier assumptions, the funnel cannot have been formed by advection from the north, but is obviously formed by a downward motion. The depression is shown, perhaps still more distinctly than on the tropopause chart, at the 300 mb. level where the temperature of Kajana (−42.7°) is remarkably high, and the isotherms show a closed maximum. At the 200 mb. level the depression is still perceptible.

The intense depression in the tropopause level is usually connected with a high-reaching low-pressure area, but in the case treated here there is, from 700 mb. upwards, a uniform westerly current rapidly increasing with height, with which the tropopause-funnel and the low-pressure area move to the east. If we examine the chart for pressure changes during the last three hours at ground level, we find that the depression lies within the area where the inclination of the tropopause is steepest and where the advection of warm air is largest at the 300 mb. level, whereas the rise in pressure lies within the area where cold-air advection is largest. The trough in the tropopause may be regarded as a type of wave disturbance at the 300 mb. level, cf. J. Bjerknes (1937), »Theorie der aussertropischen Cyklonen». To the formation of this depression advective processes contribute, which have been shown statistically by Schedler (1921) and by synoptic-aerological analysis by J. Bjerknes (1932), also as do vertical movements, which, as has been mentioned, are necessary conditions for the formation of a funnel. At a later stage, when the vertical movements have reached a maximum effect, the low-pressure area may have risen into the tropopause region and become stationary. From the situation on the 20th. April we see clearly that, although the low pressure has not reached a great height, a distinct tropopause depression can be formed and displaced. As has been mentioned above, the vertical change in the air over Kajana at 300 mb. appears to have the magnitude of 300 gm., which during the last 24 hours corresponds to an adiabatic heating of 3°, whereas the advective heating is calculated to have been 2°. The current at 300 mb. is very powerful and the area with strong warm-air advection in the stratosphere is moved to the east. In the same manner the area of falling pressure is moved to the east and with it the shallow low-pressure area at ground level. The rate at which the isallobaric regions are moved seems, however, to be considerably lower than the current at the 300 mb. level, which may be connected with persisting vertical movement at the tropopause level. Over a low-pressure area, which has risen to the 300 mb. level, the tropopause depression is displaced extremely slowly. The warm-air advection in the stratosphere is small, as are the falling tendency at ground level and the movement of the low-pressure area.

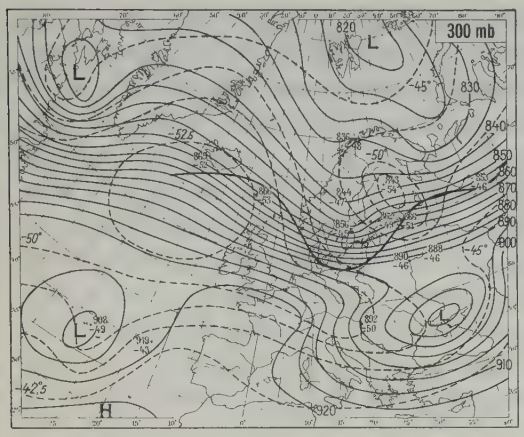
**April 21 st.**

Over the Balkans and South-Western Russia the cold air mass remains since the previous day (Fig. 11 p. 35). At Budapest a heating in the troposphere (Fig. 29) has occurred, amounting to approx. 2°. Sevastopol (see Fig. 30) shows a temperature gradient greater than the moist-adiabatic up to 3.0 gkm., whereas the relative humidity is 70—80 %. The temperature from the sounding at Sevastopol is the only one, besides that from Budapest, which forms the basis of the height-charts in the cold-air region for this day. It is of course not impossible that a chance observational error may be found in the sounding, and therefore we have tried to test the sounding with the aid of ground observations. It is to a certain extent possible to do this, if not actually in Sevastopol, at least in its proximity.

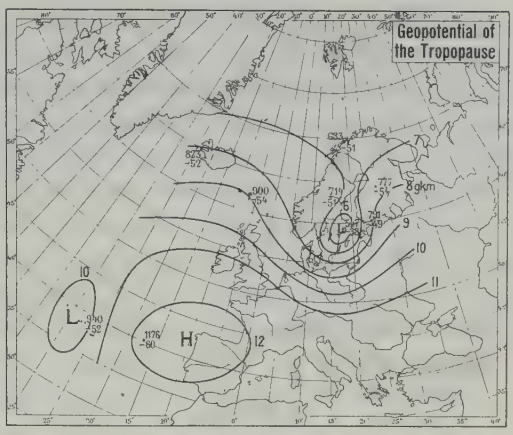
At Sofia the sky is clear excepting some Cu-clouds at mid-day. At 1300 hours GMT the temperature is 15°. The old, somewhat heated cold air is dry and the relative humidity is only 30—40 %. If we assume that a particle of air rises from the ground (550 m. above sea-level) with this condition, the condensation level will not be reached until 1 600—2 000 m. above the level of the station. The reported clouds are also Cu and Sc at 1 500—2 000 m. If we calculate the temperature at the condensation level with the aid of an adiabatic paper, we obtain the values —1.5° to —5.5°. If we assume that the temperature gradient at high levels above it is somewhat less than moist-adiabatic and thus counteracts the formation of squalls, a temperature —5.0° to —8.0° is obtained at 700 mb. In calculating the corresponding temperatures for Feodosia, 45° 02′ N, 35° 23′ E, values between —10° and —12° are obtained, and for Tarchanchut, 45° 21′ N, 32° 30′ E, —8° and —10° are found. At no place are values so low as those shown by the sounding at Sevastopol, i. e. —12°, found with certainty. It is, however, clear from the discussion that the air at Sevastopol is considerably colder than further to the north, and that a possible error cannot be large. As will be shown below, the study of the trajectories, the wet-bulb potential temperature and mixing ratio support the view that the sounding values from Sevastopol are correct.

Whereas the observations of the 20th. did not show with certainty whether the seclusion of cold air had continued right down to the 700 mb. level, there is no doubt that this is the case on the 21st. (see Fig. 29). At 700 mb. Sevastopol has a temperature of —12°, whereas Smolensk and Orsha have —7° and Orenburg —5°. At 500 mb. the temperature difference is still greater; Smolensk has —20°, Orsha —21° and Orenburg —19°, whereas Sevastopol has —29°.

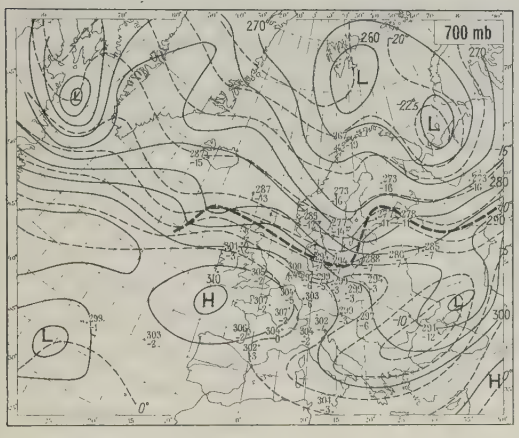
It is remarkable that the more or less stationary cold air mass in the south has not to any large extent been heated since it flowed down over the North Sea between the English high-pressure area and a terminating cyclone further to the east four days earlier. The insignificant heating is no doubt connected with the distribution of pressure. The pressure is comparatively low, approx. 1 010 mb., as compared with approx. 1 030 mb. above Western France. In South Russia there is no subsidence, which was actually to be expected, considering the fact that the cold air is relatively heavy. On account



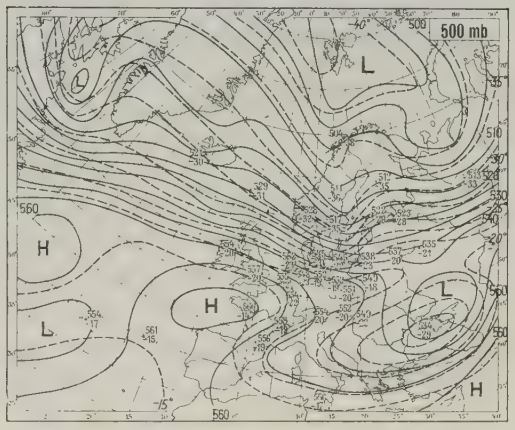

c) 300 mb.




d) the tropopause.




a) 700 mb.




b) 500 mb.

Fig. 29. Geopotential charts for April 21st. 1939.

of the absence of any considerable subsidence the clouds, which often are of a close Ac-type, are of a lasting character and prevent heating through radiation. Even if there are no clouds in some minor districts, the air in the lower layers is so dry, as is the case at Sofia, that the condensation level will lie very high. A heating of the cold air at high levels by convection currents (squall clouds), which is normal for this season, can therefore only have a very insignificant effect.

To the north of the Sea of Azov there is a precipitation area connected with a stationary depression. The pressure at the centre goes down to 1 007 mb. The precipitation has the character of rain from Sc- or As-clouds formed by upward gliding. At high levels there seems to be cold air advection, which could cause instability and light rain connected therewith. The aerological material does not, however, allow a closer analysis.

To the south of Novaya Zemlya we find the depression which on the 20th. had its centre over Northern Finland. At Syktyvkar (Fig. 30) we find at 1.0—2.5 gkm. a disturbance in the sounding which might well correspond to the cold-front at the ground. The wet-bulb potential temperature at the upper level of the front is as low as 2.3°, which best corresponds to the conditions in the arctic front on April 20th., although this front cannot be found on the ground chart. At the 700 mb. level, which should thus lie up in the polar air, the temperature is —16°, corresponding to that of Kajana on the previous day (see also Fig. 43 a p. 103), and at 500 mb. the temperature is —33° which also roughly corresponds to the temperature of the previous day at Kajana (—32°). The previous southern warm-front seems to have completely disintegrated; it is, however, faintly marked on the ground chart.

To the south of the Gulf of Finland we find the wave disturbance which on the 20th.

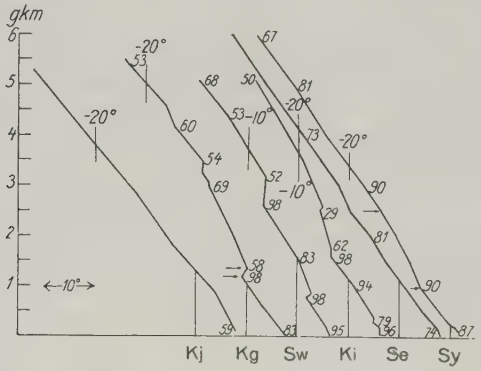



Fig. 30. Some temperature-height diagrams on April 21st. 1939. Kjeller, Königsberg, Swinemünde, Kiel, Sevastopol and Syktyvkar.

was observed over South-Western Norway. In its eastern part a distinct precipitation area of upward gliding character can be observed, whereas in the west the cold-front is diffuse at 0700 hours GMT. At 1300 hours GMT, however, general showers occur within the cold-air region near the front. At Helsingfors (Fig. 27) one might expect a front-surface at a height which, with a normal inclination of the front, i. e. about 1/100, would be at approx. 3 gkm. Not until 5 gkm, can a faint discontinuity be observed in the temperature-height curve. If this were the front surface the slope of the front would amount to approx. 1/50. If we attempt to follow the trajectories (see Fig. 43) and the distribution of the wet-bulb potential temperature, we reach the apparent conclusion that the air above the disturbance layer is also polar air, i. e. air which on the previous day was to be found to the north of the front above the North Sea. The value of the wet-bulb potential temperature at the upper level of the disturbance is 8°, whereas it was 10° at the starting point of the calculated trajectory 24 hours earlier. Such a fall in the wet-bulb potential temperature may have been caused by an upward

motion. On the morning of the 20th. there was considerable precipitation in Norway, indicating a general elevation. In any case it is clear that the air at high levels to the east of the Baltic Sea is warmer than to the west of it and that the temperature difference is largest in the vicinity of the Gulf of Finland. It is possible that Stockholm has a pressure-error of 10 to 20 mb., and may therefore be 1°—2° too cold in the troposphere. No correction has been made on the charts, as the extrapolated value of the geopotential at 100 mb. appears to be reasonable without any correction.

At Stockholm (Fig. 27) there is an almost isothermal layer between 5.5 and 6.2 gkm. This might be regarded as the cold-front, but the value of the wet-bulb potential temperature is fairly low, only 7.5°, and the starting point of the trajectory 24 hours earlier (Fig. 43) lay far outside the front and, finally, the slope of the possible cold-front would only be 1/120, whereas the hypothetical front at Helsingfors would have the slope 1/50. It is not in accordance with earlier experiences that the cold-front at so late a stage of a cyclone should have such a small inclination (and above all not less that of the warm-front). We therefore assume that this is a question of a newly formed tropopause, and our view is supported by the values of the temperature in the stratosphere obtained at Stockholm.

As mentioned above, Palmén (1933) has indicated the aid in the analysis which can be obtained from the values of the potential temperature $\Theta$ at the tropopause levels (cf. Table VI, p. 69). The value 325° at Helsingfors on the 21st. corresponds to the values in **T** on the 19th. and 20th. In addition there is a lower tropopause with $\Theta = 308°$. At Stockholm the value of $\Theta$ for the lowest tropopause is as low as 292°.

Kajana must be too cold or Helsingfors too warm, as there is no satisfactory agreement on the 100 mb. chart (not published here) between their values. Taking into consideration the Tromsö sounding, it also seems probable that Kajana is too cold. This is also indicated by the very low temperature-value at the tropopause level. However, a correction at Kajana has not been made.

A temperature difference between Helsingfors and Stockholm is also found below the disturbance level, even if it is less distinct there. The air at Helsingfors at 700 mb. is also only a few degrees colder than that of the warm-sector on the previous day, and it must have come from a region within the frontal zone, or rather to the immediate north of it. Thus we can only say with certainty about the wave disturbance that within it warm air has risen, whilst simultaneously it has cooled and precipitation has occurred. Whether the ascending rain-forming air entirely consists of the original warm air or whether previous cold air masses (**P**) have also taken part in the ascending motion, cannot be determined. To the extent they have existed, the fronts have become decidedly weaker since the previous day and the inclination of the possible front-surface to the north amounts to approx. 1/50.

Königsberg (Fig. 30) has at 1.2—1.4 gkm. an inversion which might be suspected to be the cold-front, but the value of the wet-bulb potential temperature at the upper level is only 5.0°, which is as low as that of Helsingfors at 700 mb. At 700 mb. the wet-bulb potential temperature of Königsberg is 8.2°, which must be regarded as a charac-

teristic of warm air, and therefore the air mass boundary must lie between 1.4 gkm. and the 700 mb. level. However, the front seems to have distintegrated. In any case there is an absence of distinct thermal indications of a front. At ground level the indications of fronts are also practically non-existent.

In Fig. 31 a cross-section Munich-Tromsö has been drawn. In the section the radiosounding from Erfurt on the 20th. at 2200 hours GMT has been indicated. This station

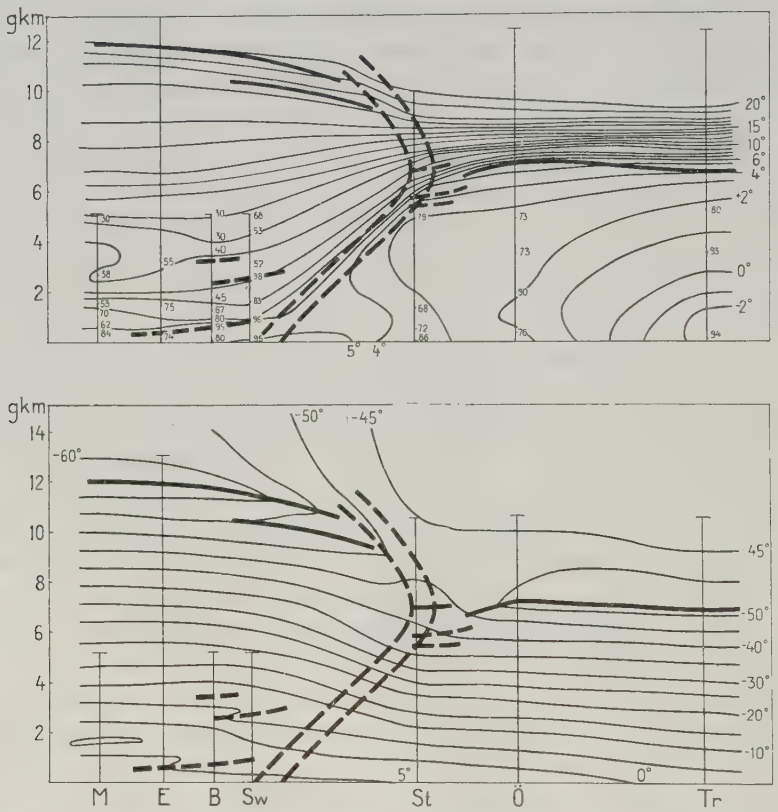



Fig. 31. Vertical sections showing temperature (C) and wet-bulb potential temperature on April 21st. Munich, Erfurt, Berlin, Swinemünde, Stockholm, Östersund and Tromsö.

is clearly too warm or has too low a pressure. The tropopause may thus actually lie some gkm. lower (at the most), but all the same it is probably high and sharp. On the figure a cold-front has been faintly marked which, if it exists at all, is very indistinct. Really distinct is the barotropy in the air masses between Stockholm and Tromsö and Berlin and Munich. Between Swinemünde and Stockholm there is a frontal zone which becomes more distinct at high levels than at levels near the ground, but there is no aerological station in the district. Several Swedish aeroplanes belonging to Swedish Airlines, which fly on the

routes Stockholm—Copenhagen and Stockholm—Berlin, have, however, given cross-sections with temperature values and cloud-information for various heights. An example of such sections and an extensive explanation of their use has been given in the report of the Aerological Commission from the meeting in Berlin on 16th.—20th. June 1939. Here we have only reproduced one of the sections (Fig. 32), which, like the others on the same day, have no hydrometeors indicated which might show some kind of front. The close temperature readings of this section show that all discontinuities exceeding a few degrees in the temperature field are impossible at the 3 000 m. level. The fairly sharp fronts which on the previous day were observed between the tropical air and the arctic air above Scandinavia have now practically disintegrated.

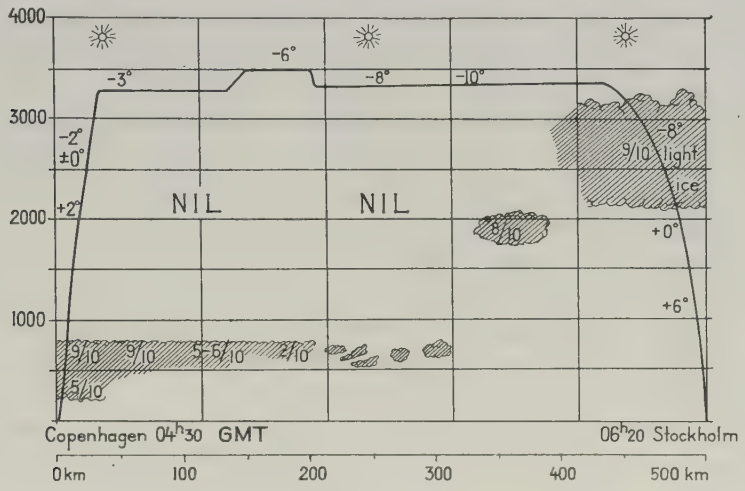



Fig. 32. Vertical section Copenhagen—Stockholm on April 21st., drawn on board a passenger aeroplane.

It is also remarkable that a rise of pressure does not occur behind the cold-front in the Baltic. It is true that the front is diffuse, but the cold-air advection is considerable. However, the pressure rises 3—4 mb. in North-Western Norway and a falling-pressure area of 2 mb. lies over North-Eastern Sweden. This fall and rise may be connected with the moving to the east of the tropopause trough over Northern Scandinavia (see Fig. 29). In the area over Finland where the tropopause topography falls and warm air advection prevails in the stratosphere, the pressure falls; further to the west the tropopause rises and simultaneously an advection of cold air in the stratosphere and the troposphere prevails. Behind the ground cold-front in the Baltic the pressure does not rise, however. The effect of cold-air advection in the troposphere is here counteracted by the effect of warm-air advection in the stratosphere. Such a stratospheric advection may, according to Thomas (1935), have a decisive effect on the pressure changes at ground level. In addition to the advective effect there are also the above mentioned (p. 57)

convergence-divergence effect and vertical movements. To distinguish these effects from each other is impossible with the material at hand. The fall and rise in pressure in North Scandinavia are, however, assumed to be a consequence of a wave in the tropopause region without any direct connection with a frontal wave in the lower troposphere. In other words, we regard the disturbance as a free upper wave, which, in spite of the quasi-homogeneity in the troposphere of the air masses on both sides of the depression, causes a certain amount of precipitation. At Riksgränsen 7 mm. and at Haparanda 1 mm. were recorded on April 21st. 1800 hours GMT.

The lower stratosphere is extremely warm. Judging from the trajectories and the wet-bulb potential temperature, the air at 600 mb. appears to have risen some hundred metres at Stockholm (even if a probable pressure error is taken into consideration). At a greater height, 300 mb., the air appears to have fallen just as much. These vertical movements must be combined with a horizontal divergence, which in this case occurs as high as the 500—400 mb. level.

The tropopause depression is very deep at Stockholm. There a number of multiple tropopauses have been formed, of which the lowest extends as far down as 5.47 gkm. and is considerably lower than the distinct tropopause at Tromsö in the far north. This is a good illustration of the fact emphasized by Palmén that vertical movements have played a considerable part in the formation of the tropopause depression. For the sake of comparison we refer to Van Mieghem (1937), who found a tropopause as far to the south as at Uccle at 6.0 gkm., and Palmén (1933), who found a tropopause at only 5.1 gkm. at Sealand. Sharply contrasted to the low and warm tropopause of Stockholm is Erfurt's sharp, high and cold tropopause.

Let us return to the consideration of the troposphere and the front in Germany, which has been faintly marked out on the ground chart, although its existence can no longer be determined from the observations. Further to the west in Scotland the temperatures are 3—5° lower than at the north coast of Ireland. Observations from ships at 56°.5 N, 19° W and 55° N, 12.5° W indicate the existence of a wave disturbance, which has been plotted on the ground chart. Inside the warm-sector drizzle is reported, and after the cold-front a shower and also falling temperature. The fall in pressure is considerable, 1.1 to 1.6 mb. in 3 hours inside the warm-sector, which indicates a deepening. The supply of cold air over Scandinavia in advance of the wave disturbance and over the Atlantic behind it, are both favourable for the development of the disturbance. The warm-sector air is best studied with the aid of the sounding at Aldergrove (Fig. 34), which shows that the air mass at layers up to approx. 2 gkm. is fairly cold. It is air which has passed round the high-pressure area over Southern England and thereby assumed a temperature which in the first place is influenced by the temperature of the sea-water. As the air has not been further to the south than 42°—40° N the wet-bulb potential temperature has not been higher than 7—8°. At the 700 mb. level and higher the air has come from the west and earlier from the south-west, and thus has a completely different origin from air at a lower level, although they now together form the warm-sector. Between Aldergrove, which lies completely within the warm-sector, and Thors-

havn, which seems to lie completely within the cold air, any warm-front must exist. The perpendicular distance between the front at ground level and Thorshavn amounts to approx. 500 km. At Thorshavn there is no disturbance-layer in the lower parts of the sounding which could be interpreted as the front in question. At 5 220 gm. the temperature is given as —29.6° and at 5 370 gm. as —31.8°. One of these values is incorrect, but the error is of minor importance. Not until 7.9 gkm. does a noticable decrease occur in the lapse rate. It is possible that this is the normal tropopause, but above this lowest tropopause there is another one at 9.0 gkm., the temperature of which is as low as —53.8° with a potential temperature of 315.5°. This value of the potential temperature is also considerably lower than that which is characteristic of **T**. As mentioned above, Helsingfors has the value 325°. We might imagine that the front touches the vertical line through Thorshavn at a level of approx. 7.9 gkm. just as the warm-front at Helsingfors at approx. 6 gkm. on April 19th. If we assume a course like this a slope of the front surface amounting to $\frac{7.9}{500} = \frac{1}{65}$ is obtained, which is an unusually large inclination for a warm-front.

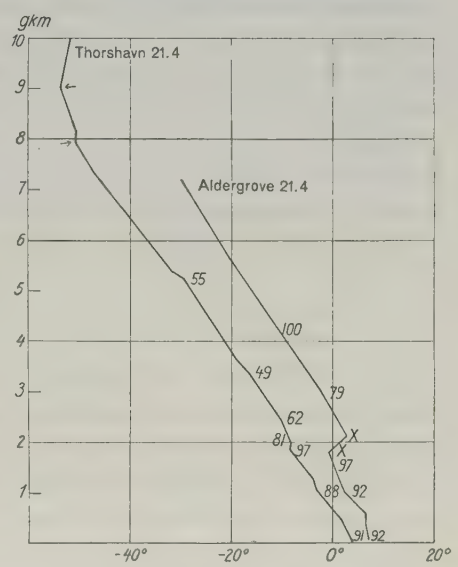



Fig. 33. Temperature-height diagrams for Aldergrove and Thorshavn on April 21st.

As **T** at Aldergrove does not reach ground-level but is first found at 2 gkm., one might assume the existence of two fronts, of which the lower one, between two different polar air masses, only reaches a height of some kilometres, and the higher one between the warm polar air and the tropical air touches Thorshavn at 7.9 gkm. with a slope of approx. 1/90. J. Bjerknes and C. L. Godske (1936) show on a theoretical basis that a large inclination of the front is favourable to cyclogenesis, and this theory might thus be regarded as applicable to the wave disturbance west of Scotland. For several reasons, however, we must question whether there actually is a front between Aldergrove and Thorshavn.

From the situation on the 17th. April we have seen that the existence of a front is not a necessary condition for the formation of a wave disturbance. On that day there was a wide frontal zone, within which the wave was formed and continued to exist. On the 21st. it is not possible to determine whether there is a front or not, but it is certain that a large number of solenoids exist within the area between Thorshavn and Aldergrove (see Fig. 33), and thus that conditions for cyclogenesis exist. According to Bjerknes and Godske the concentration of solenoids to a sharp front is favourable to rapid deepening and motion, and they regard frontogenesis as the primary condition, and cyclogenesis as the secondary one. Others, such as Kobayasi (1923),

have, on the other hand, tried to explain frontogenesis as caused, in certain cases, by cyclogenesis.

Bergeron (1928) has treated earlier works on the formation of fronts and has himself made a considerable contribution to our knowledge of the influence of the deformative fields on fronts. More recently Petterssen (1935) has given a more complete mathe-matical description of frontogenesis and frontolysis as consequences of kinematic deformation. As a special case we shall describe here the effect caused by a revolving motion.

The description is given in connection with the development of the wave disturbance to the west of Scotland on the 21st. and 22nd., for which days comparatively abundant synoptical material is available, which may illustrate the similarity between the schematic description and reality. We assume that in a parallel uniform current of air the isotherms are parallel with the isobars and equidistant like these. Superimposed on this current we imagine a revolution which is more or less a simple vortex, i. e. the velocity ($v$) multiplied by the distance from the revolution centre ($r$) is constant. A simple vortex would give an infinite velocity at the centre. We therefore change the limiting conditions to better agreement with reality, and instead of the angular velocity being $\omega = \frac{v}{r} = \frac{k}{r_2}$ we insert a constant $a$ in the expression for $\omega$ and obtain

$$\omega = \frac{k}{r^2 + a}$$

With this formula the position of the isotherms has been calculated after certain times. We reproduce here a picture (Fig. 34) of the condition after 24 hours with a rotational wind velocity of 2 m. per sec. at a distance of 200 km. from the centre. It is then clear from Fig. 34 how the isotherms kinematically approach each other through circulation within certain districts, whereas they move away from each other in other districts. The positions of these frontal zones are remarkably similar to the conditions in a half-occluded cyclone, although the vertical air movements, which we have disregarded in the kinematical diagram, must have a considerable influence in a real cyclone, as they may cause a levelling out of temperature contrasts.

In nature we seldom find complete uniformity or symmetry. Many accumulations of isotherms may for instance have been caused by radiation [Gold (1935)], by subsidence and rain, [J. Bjerknes (1926 and 1930)], by the influence of a previous deformative field, by orographic effects [Bergeron (1928)] or in other ways. These accumulations of isotherms may therefore be the beginnings of later fronts, and it is therefore easy to obtain several fronts in a cyclone, which are partly parallel with each other. These fronts are, according to the above mode of treatment, completely or partly caused by circulation. The increased circulation is, according to general opinion, the consequence of an endeavour of the colder air to force the warmer air up to a higher level. This becomes possible owing to the pressure distribution, which carries colder air to the south in the western part of the wave. The pressure distribution is an extremely complicated question which is influenced by events at very distant places and therefore cannot easily be surveyed. We may imagine that a wave motion in the tropopause region of comparatively small

extent, i. e. the remains of a previous tropopause depression or trough, causes a rise and fall motion. This motion releases the cyclogenesis where a sufficient number of solenoids exist, but no observations are available for such an extensive investigation of the character of the wave disturbance. A comparison with the wave disturbance of April 17th. shows that the numbers of solenoids in both cases were roughly the same, and that the pressure distribution on the 21st. was more favourable for cyclogenesis. On the 17th. the wave-front was almost parallel to the isobars in a powerful current, whereas the wave on the 21st. was favoured by the warm high-pressure area to the south of the warm-front and the cold high-pressure area north of the cold front, which was probably formed fairly independently of the wave. In addition it may be pointed out that the slope of the tropopause on the 17th. was very large within the disturbance area and fairly moderate on the 21st. and that the height of the tropopause on the 17th. was very small, whereas it was relatively great on the 21st. even north of the ground wave.

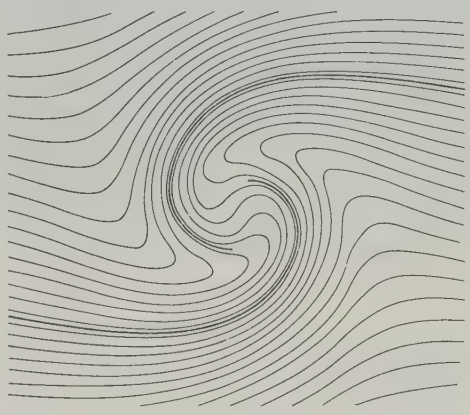


Fig. 34. The course of previously rectilinear isotherms after a supposed rotatory motion.

On the 22nd. April we return to a comparison between the schematic figure (34) and the geopotential chart for 700 and 500 mb.

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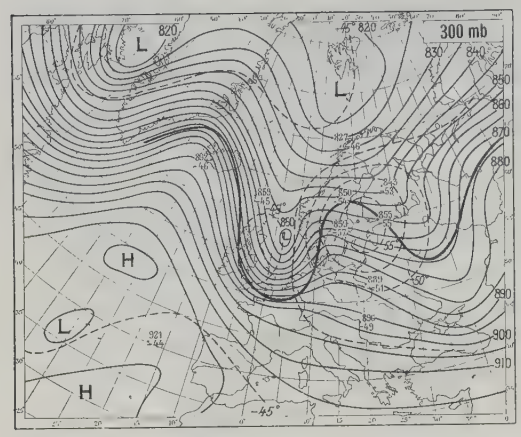
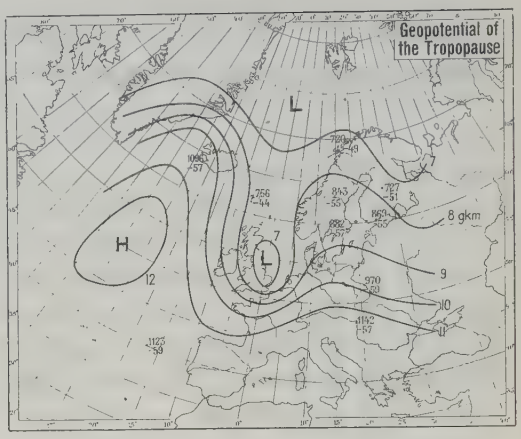
To the south of the Azores there is still a low-pressure area. In the lower troposphere the temperature differences between Carimaré and Angra are insignificant. At 700 mb. Angra is 1° warmer, at 500 mb. 2° colder than Carimaré. At 300 mb. Angra is 6° colder. The tropopause at Angra lies at 9 400 gm. and has a temperature of — 52°, whereas over Carimaré the tropopause lies at 11 670 gm. with a temperature of — 59.5°. The greatest temperature contrast is to be found at 200 mb. where it exceeds 10°. Thus the depression appears to be firmly anchored in the tropopause region. Considering that the temperature contrasts at ground-level have also been moderate previously, it is conceivable that the formation of the depression is also a consequence of changes in the tropopause level. The wind is slight at all levels and this enables the depression to be stationary.

### April 22nd.

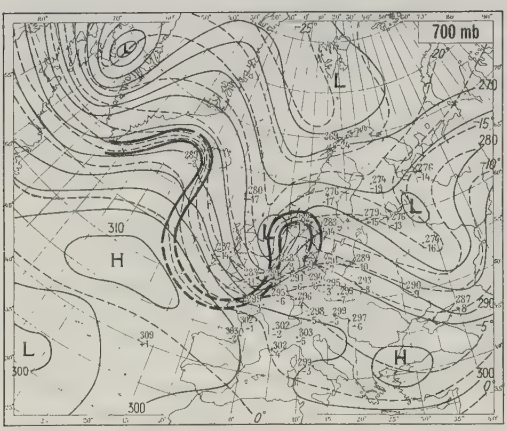
The depression over the Gulf of Finland on the 21st. has deepened and moved to the east and lies with its centre near Moscow. The position of drawn-out fronts is shown by



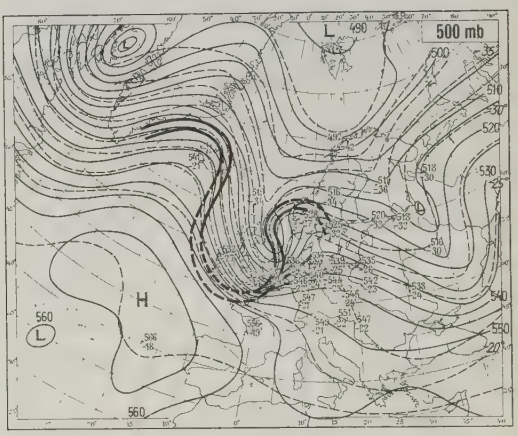

c) 300 mb.




d) the tropopause.




a) 700 mb.




b) 500 mb.

Fig. 35. Geopotential charts for April 22nd. 1939.

the ground chart (Fig. 12 p. 36). The secluded cold air, which on the 21st. still had a very low temperature in South-Western Russia, is difficult to find on the 22nd., (see Fig. 35). It is possible that the cold air has split into two parts, of which the more southerly one has moved straight to the south over Greece and has been heated partly from the ground and partly by subsidence, which presumably occurs, as the air now lies in a high-pressure ridge with rising pressure. Another part of the cold air has been carried more to the north-east and has been blended aloft with the new cold air flowing down from the north-west. At Rostov the lapse rate of the air in advance of the ground cold-front is only slightly less than the moist-adiabatic, and at Stalingrad as well within the warm-sector there are already Cb-clouds at 10 o'clock in the morning, local time, with

a ground temperature of 6°, showing that there is cold air at a high level. Further to the north inside the warm-sector the ground temperature is higher, but clouds of the types Cu, Sc and As indicate a greater stability and thus a higher temperature at high levels. The ground warm-front has nothing in common with the warm-front connected with the wave disturbance over the Baltic on the previous day. This warm-front should, if it could be localised, lie five or ten degrees further to the north to be in agreement with the current. The warm-front which has been drawn must be regarded as a convergence line, caused by the pressure distribution, and which may develop into a front. What can be aerologically proved is that the warmer air in the depression over Russia moves upwards and causes precipitation in the central parts of the depression.

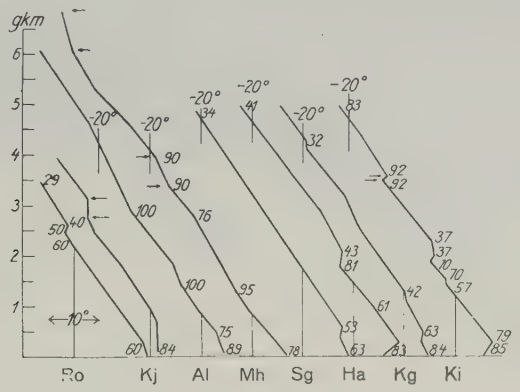



Fig. 36. Some temperature-height diagrams on April 22nd. Rome, Kjeller, Aldergrove, Mildenhall, Soesterberg, Hamburg, Königsberg and Kiel.

At Archangel the temperature at 700 mb. is — 14° in contrast to — 16° at Moscow. Sverdlovsk, 55° N., 40° E. has — 5° (outside the region of the chart).

The wave disturbance to the west of Scotland has deepened during the past 24 hours from approx. 1 012 mb. to 990 mb. The centre of the relatively powerful cyclone lies over the North Sea and moves to the east continuously deepening. As usual the aerological material obtainable is far from sufficient for a complete examination of the cyclone, but with the given material some questions of great interest may be treated.

On the 21st. no front could be observed over Germany; this also applies to the 22nd., in the eastern parts of the country. At 700 mb. the temperature falls continuously from Munich — 5°, over Breslau — 7°, Warsaw — 8°, Königsberg — 10°, Stockholm —14°, Helsingfors — 15°, to Kajana — 19°. Further to the west, the air at Hamburg is under the influence of subsidence, but the aeroplane report says, »Fern im Nord bereits ab 4 000 m Ac und As mit Lücken am E-horizont». From Kiel we hear: »Ab 4 000 m über Gipfel (5 000 m) 10/10 dünner geschichteter Ac, As, daraus leichter Schneefall bis 3 200 m herab». The temperature curve from Kiel (Fig. 36) shows a small inversion between 3 500 and 3 600 gm. in connection with high humidity, so that we must assume that

the most southern part of an actual warm-front is to be found there. From Southern Sweden there are no soundings, but cross-sections from passenger planes give us certain information. A plane which started from Copenhagen at 0435 hours GMT and arrived at Stockholm at 0630 hours GMT records at a constant level of 3 200 m. a slow cooling towards the north. Excepting some high clouds only Sc-clouds, with their upper level at 1 500 m, are recorded from the first part of the route, and 5/10 Ac or As at 3 500 m. at the very beginning of the route. These latter clouds might be a presage of the warm-front. Ci- or Cs-clouds in connection with the warm-front were not observed from the aeroplane, nor were they reported from the ground stations. The section drawn on board an aeroplane starting from Malmö at 1051 hours GMT and landing at Stockholm

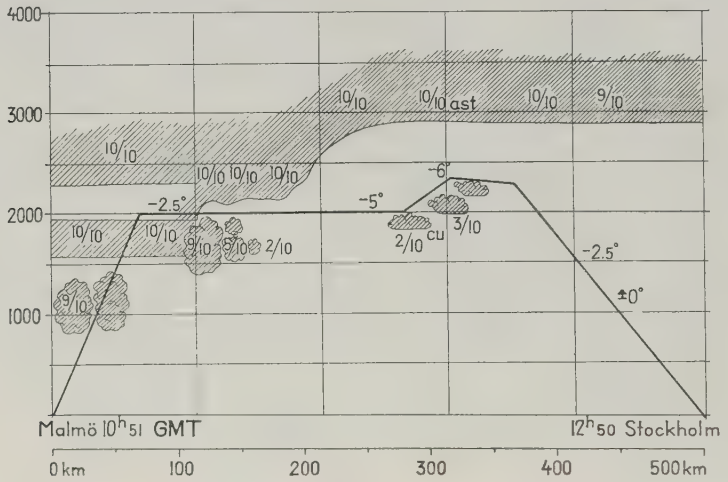



Fig. 37. Vertical section Malmö—Stockholm on April 22nd., drawn on board a passenger aeroplane.

at 1250 hours GMT is reproduced in Fig. 37. Stratified clouds are reported at the beginning of the route, with cloud gaps at 2 000 m. The front was crossed at 50 km. and at 100 km from the start, after which the rising of the front to the north was observed from the aeroplane. As the front has moved from west to east while the plane travelled north-north-east, the slope of the front has become apparently smaller than it is in reality. Temperatures from the section show —2.5° at 60 km. from Malmö and at a height of 2 000 m, and —5° at 260 km. from Malmö at the same height, from which we see that the temperature contrasts are small. The differences in the wet-bulb potential temperature are certainly larger, but the front can still be said to be very faintly developed. Further towards the centre there is a sounding from Kjeller near Oslo (Fig. 36). It shows, at 2 500—3 150 gm., a disturbance in the course of the temperature curve so that isothermal conditions prevail within the layer. Unluckily the humidity record has been lost, but there is good reason to believe that the warm-front is to be found

here (cf. Fig. 38). A subsidence inversion within the cyclonic current is less probable. It is difficult to determine the inclination of the warm-front, as the position of the ground front is uncertain. However, the front has a great inclination, which is probably more than 1/100 in the southern parts at Kiel and Copenhagen and slightly less to the north at Kjeller. At the time of this sounding Stockholm is more than 800 km. away from the

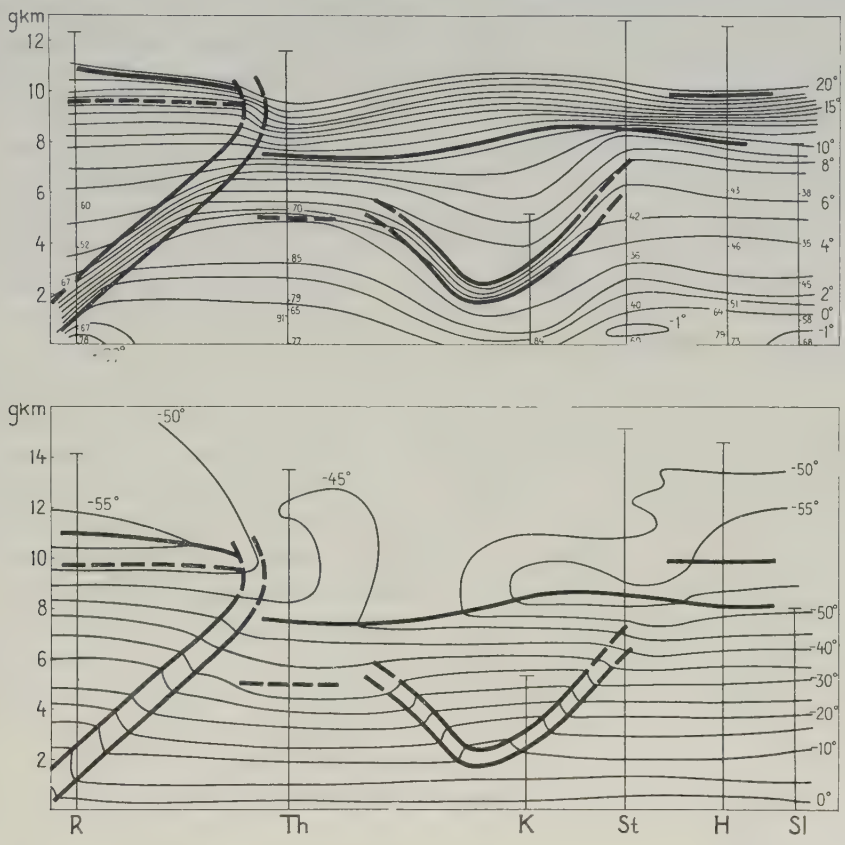



Fig. 38. Vertical sections showing the temperature (C) and the wet-bulb potential temperature on April 22nd. Reykjavik, Thorshavn, Kjeller, Stockholm, Helsingfors and Slutsk.

front, and with the great inclination observed it is less likely that we should find the front in the Stockholm sounding even if the front extended as high as the tropopause level. Stockholm, as well as Helsingfors, has a cold and comparatively high tropopause, no doubt connected with their position in the high-pressure ridge between the low-pressure areas over Russia and the North Sea. The height of the tropopause does not appear to have any direct connection with the approaching disturbance from the west,

which is seen from the fact that the potential temperature in the tropopause is relatively low (cf. Tab. VI, p. 69).

If we try to find the cold-front the task is perhaps still more difficult. Showers over the British Isles obviously show the existence of cold air, as do the soundings at Mildenhall and Aldergrove. The cold air does not appear to have reached Soesterberg. Thus the front must run between Soesterberg and Mildenhall. Near the centre of the cyclone, the pressure still falls far behind the cold-front at ground level in connection with the tropopause depression, and does not rise again until the tropopause rises above and behind the backbent occlusion [cf. Bjerknes-Palmén (1937)]. In the sounding from Mildenhall the lapse rate is slightly diminished between 3.4 and 4.0 gkm. This layer may be regarded as the cold-front the slope of which should then be 1/65. This is a normal value. The air above this layer, however, is so cold and originates from such a northerly region (see Fig. 43 b) that we cannot interpret it as warm air. We suppose that it is a beginning of a subsidence inversion forming in the cold air. In the ascent at Mildenhall (Fig. 36), there is also an almost isothermal layer at 6.0—6.8 gkm., which may be regarded as the cold-front or as a layer over a newly formed tropopause. If the probable course of the front at 0700 hours GMT is drawn, and consideration is taken of the fact that the observation at the 6.8 gkm. level was made exactly at this time, a slope of 7/200 or approx. 1/30 is obtained. This inclination is abnormally great, and we therefore assume that the front already vanishes before it reaches such a high level as 6 to 7 gkm., which is a fairly usual occurrence at a cold-front. See, for example, Nyberg-Palmén (1942). We regard the discontinuity in the temperature curve as a tropopause, the height of which, 6.0 gkm., is not abnormally low near the bottom of the tropopause depression. Compare the height of the tropopause at Stockholm (5.47 gkm.) on the 21st.

The air lying over Mildenhall on the 22nd. at 400 mb. (6.8 gkm.) has a wet-bulb potential temperature of 11°. The trajectory (see Fig. 43 d) appears to originate at a point approx. 60° N 35° W, where at the same level the wet-bulb potential temperature was approx. 8° on the 21st. The value 11° is not found until 330 mb. on the 21st., and the air has thus fallen during the 24 hours between the 21st. and 22nd.

Bjerknes and Palmén (1937) have described the aerological conditions at a cold-front in a situation which is very similar to that over the Channel and England on the 22nd. Of two soundings at Uccle, one was made two hours before the passage of the cold-front and the other four hours after. The latter shows, up to a level of 2 gkm., a slightly lower temperature than the former. After this the second sounding passes through a very faintly marked cold-front. Above this front the temperature differences between the soundings increase with height. The cold air over the front, which is dry and apparently has subsided, is regarded by Bjerknes and Palmén as cold tropical air, so greatly cooled by radiation when passing through northerly regions before sinking, that in spite of the Föhn effect it is cold. With the aid of observations from Reykjavik and Thorshavn we shall here attempt to determine the origin of the air mass, which, in analogy with the case described by Bjerknes and Palmén, should be regarded as cold tropical air. It is certain that a downward motion has occurred, causing a rise in the wet-bulb potential

temperature at fixed levels, and a new formation of the tropopause, but we regard the sinking air as polar air. The value of the wet-bulb potential temperature at 330 mb., 11°, is too low to characterize **T**, and is fairly typical for polar air. In cases like these the cold »front» is a zone with successive cooling within an almost vertical layer, and the cold air, **P**, may extend right up to the stratosphere, as was already shown by Douglas (1925). The front can also be locally strengthened at ground level and cause squalls and violent showers. Thus at Hamburg squalls of 34 m. per sec. were recorded, and a fall in temperature of several degrees occurred within a few minutes.

If we compare the appearance of the schematical isotherm diagram (Fig. 34) and the chart for 700 mb. on the 22nd., we find a striking similarity. There is no warm-front in the eastern outskirts of the true cyclone, but it can be faintly discerned on and beyond the line Kiel-Copenhagen, and is fairly distinct at Kjeller. The course of the isotherms is also similar to that in the schematical figure. Even at 500 mb. the similarity is striking. The vertical movements inside the cyclone, which attempt to dissolve the fronts, have an influence which is insignificant in the outer parts of the cyclone, but which increases towards the centre. The cyclonic frontogenetic effect is, as Fig. 34 shows, greatest not far from the centre. A combination of these opposing effects gives a maximum density of isotherms at a varying distance from the centre. The longer the vertical motion continues, the further from the centre will the most clearly marked part of the front be found, whereas the inner parts of the cyclone become more and more homogeneous.

In the cyclogenesis and the subsequent occlusion the air in the warm-sector rises, and the surrounding cold air sinks. The result is that the mutual centre of gravity of the air masses in the cyclogenesis and the occlusion is lowered, and that the potential energy released in this way is converted into kinetic energy. The wind speeds calculated by Margules (1905) show that the released potential energy (in dry air), in imaginary cases corresponding with reality, is sufficient to cause the winds that occur. Refsdal (1930) has shown the importance of the potential energy in moist-labile air. If we follow the air currents in the cyclone investigated here, we find the expected confirmation of our assumptions about the source of wind energy. The development of the cyclone, however, includes certain complicated factors, and a more detailed description is therefore justified.

In the warm-sector on the 21st. high temperature values were obtained at Aldergrove as well as Mildenhall, where at 700 mb. the wet-bulb potential temperatures calculated from the given temperatures were 12.4° and 13.6° respectively, and, corrected according to Table III p. 11, 11.6° and 12.8°. We follow the trajectory from Aldergrove and find that it ends in Southern Sweden (see Fig. 43 a). In regions where changes of pressure are rapid the determination of the trajectory is uncertain, but as a southern boundary for the end-point of the gradient trajectory of the 22nd. 55° N. can be given. The wet-bulb potential temperature in Southern Sweden, and even at Hamburg, is several degrees lower than at Aldergrove on the previous day. At 700 mb. over Hamburg the value is 7.5°, and further to the north it is still colder.

We shall first attempt to explain the cooling as a consequence of pressure decrease.

The pressure at a certain geopotential level $\Phi_1$ is $p_1$. If the pressure at this geopotential level is reduced to $p_2$ we find the pressure $p_1$ at a lower geopotential level $\Phi_2$ such that

$$ln \frac{p_1}{p_2} = \int_{\Phi_2}^{\Phi_1} \varrho d\Phi$$

Thus, at a fall in pressure the geopotential falls at each pressure level, and on the height-charts, which are made for stationary pressure levels, the falls of pressure resemble areas with a falling geopotential. If the lapse rate $\frac{\partial T}{\partial \Phi}$ is equal to the moist-adiabatic gradient $\gamma$ the value of the wet-bulb potential temperature in a fixed pressure level remains unchanged by diminishing pressure. If $\left|\frac{\partial T}{\partial \Phi}\right| < \left|\gamma\right|$ (moist-stable stratification) the wet-bulb potential temperature will fall with diminishing pressure. If, finally, $\left|\frac{\partial T}{\partial \Phi}\right| > \left|\gamma\right|$ the wet-bulb potential temperature will increase with diminishing pressure.

It is thus clear that a fall in pressure causes, from a qualitative point of view, the same change in the wet-bulb potential temperature at a certain pressure level (e. g. the 700 mb. level) as an upward air motion. The same is true regarding a qualitative agreement between a downward motion and a rise in pressure.

A quantitative comparison shows that a fall in pressure amounting to 20 mb. at a height of about 3 gkm. corresponds to an upward motion of approx. 180 gm. A fall in pressure of 20 mb. at the 3 gkm. level is exactly what occurred in the 24 hours between 0700 hours GMT on the 21st. and the 22nd. April in the mobile low-pressure centre, on account of the deepening. At a fixed place in the centre of the cyclone on the 22nd. the pressure fell considerably more than in a volume of air which followed the air current, but this is of no importance in the present connection.

The fall of pressure in the centre could explain a lowering of the wet-bulb potential temperature from 11.6° (at Aldergrove at 700 mb., i. e. 3 010 gm.) on the 21st., to 10.9° (which refers to Aldergrove at the height of 3 010—180 gm.). Actually the fall of pressure in air which has moved from Aldergrove to South Sweden is only approx. 10 mb. (see the ground chart for the 21st. and 22nd., Figs. 11 and 12). This fall of pressure corresponds to a vertical motion of about one hundred gm. and the lowering of the wet-bulb potential temperature is then only from 11.6° to 11.2°.

If we attempt to explain the fall of the wet-bulb potential temperature as the result of an upward motion we must try to find the height at which the wet-bulb potential temperature reached the value 11.6° on the 22nd., in order to be able to determine the magnitude of the vertical movement. The value 11.6° is not reached until the level above the maximum height of the soundings in Northern Germany. In Hamburg the value at 500 mb. is 10.1°, and it increases fairly slowly with height. The vertical motion must have reached a height of 3 km. at least, if such a fall of the wet-bulb potential temperature is to be explained. However, such an upward motion of an air mass which, according to observations, was already almost saturated with vapour before the ascent,

must cause considerable precipitation, according to a rough estimate an average of at least 10 mm. in the region covered by the precipitation zone. Actually no precipitation whatsoever was recorded in Northern Germany, and the vertical motion must therefore have been insignificant. Instead, at Hamburg and still more at Cologne the aeroplane soundings actually indicate subsidence in large layers.

Neither can a cooling of the air by radiation explain the low value of the wet-bulb potential temperature, for such a powerful general cooling of the air would cause a precipitation of water of the same order as that calculated to be given by a vertical motion.

Now it may be of value to examine the observations more closely. The soundings in North-Western Germany on the 22nd. are many, and show very good agreement. There is absolutely no reason to expect any considerable errors in these. The English soundings at Aldergrove and Mildenhall lie further apart, but on the 21st. at 0600 hours GMT they agree well with each other and with the soundings made at the same place at 1200 hours GMT on the same day. Chance errors are therefore unlikely. Systematical errors occur in the height-chart and in the cross-sections, but as mentioned above (p. 12), they are small and generally of minor significance. In discussing the motion of the air, corrected, lower values of the wet-bulb potential temperature have been used.

There is thus no reason to expect the corrected English soundings to be too warm on the 21st. April; we can assume instead that the humidity is incorrect, but let us first examine another possibility of explaining the cold region in Southern Sweden and Northern Germany.

When a low-pressure area is formed, air must be removed by vertical movements and divergence at certain levels. On the basis of statistical material from England, Palmén (1932) has calculated the magnitude of the vertical motions in the formation of an average cyclone. On the basis of Palmén's work, Van Mieghem (1939 D) has calculated that in the formation of the same average cyclone air has poured into the low-pressure area at the layers 0—3 km. and 11—18 km., while air has poured out of the depression at 3—11 km. With regard to these results we assume that in the cyclone treated here ån outflow has occurred in a layer extending several kilometres above the 800 mb. level.

In calculating trajectories it has been assumed that the gradient wind equation is valid, and that the wind has followed the isogeopotentials.

$$2\,\omega\, v \sin\varphi \pm \frac{v^2}{r} = -\frac{1}{\varrho}\cdot\frac{\partial p}{\partial r}$$

Here we have only calculated with the normal acceleration $\frac{v^2}{r}$ and have disregarded the tangential horizontal acceleration and the vertical acceleration.

The complete horizontal equations of motion in a cartesian system of co-ordinates with the axes $x$ and $y$ is, if $v$ represents the wind velocity, $\omega$ the angular velocity of the earth, $\varphi$ the latitude, $\varrho$ the density of the air and $\frac{\partial p}{\partial a}$ the change of pressure per unit length:

$$\frac{dv_x}{dt} - 2\,\omega\, v_y \sin\varphi = -\frac{1}{\varrho}\frac{\partial p}{dx} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$\frac{dv_y}{dt} + 2\,\omega\, v_x \sin\varphi = -\frac{1}{\varrho}\frac{\partial p}{\partial y} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

The components of the geostrophic wind are

$$V_x = \frac{-\frac{1}{\varrho}\frac{\partial p}{\partial y}}{2\,\omega \sin\varphi} \qquad V_y = \frac{\frac{1}{\varrho}\frac{\partial p}{\partial x}}{2\,\omega \sin\varphi} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

From the equations (1), (2) and (3) a relationship between the acceleration, the true wind and the geostrophic wind is obtained:

$$\frac{dv_x}{dt} = 2\,\omega \sin\varphi\,(v_y - V_y) \text{ and } \frac{dv_y}{dt} = -2\,\omega \sin\varphi\,(v_x - V_x) \quad \ldots\ldots\ldots \quad (4)$$

From this we see that the vector difference $v - V$ lies perpendicularly to the left of the acceleration vector. The scalar quantity of the vector difference equals the acceleration vector multiplied by $\frac{1}{2\,\omega \sin\varphi}$. This result has been given by J. Bjerknes and E. Palmén (1937), who have also applied the results to a synoptical situation. Another application has been shown by Nyberg and Palmén (1942).

If we assume the true trajectory in the 700 mb. level to have been such that the air at Aldergrove has been carried to South-Western Germany or North-Eastern France, where the value of the wet-bulb potential temperature of the 22nd. roughly corresponds to the value at Aldergrove on the previous day at 700 mb., we can calculate the approximate acceleration. For the proximity of Aldergrove a wind strength of 15 m. per sec. is calculated on the 21st. at 3 000 m. The wind strength in South-Western Germany on the 22nd. amounts to approx. 5 m. per sec., which involves an approximate retardation of 10 m. per sec. in 24 hours or 1/8 640 m. per sec$^2$.

From the calculated geostrophic wind in the direction 280° and the acceleration vector, which has been roughly calculated as the acceleration of the geostrophic wind $\frac{dV}{dt}$ instead of the acceleration of the true wind $\frac{dv}{dt}$, a true wind is obtained which deviates 30° to the right from the geostrophic wind, and this true wind would bring us straight to the point we assumed as the end-point of the trajectory. The correspondence would have appeared to be complete, if pilot-balloon observations had not been available. These, however, do not confirm the calculations made above. The measured wind strengths near Aldergrove, at Manchester and at the end-point of the trajectory in South-Western Germany, Friedrichshafen, actually show good agreement with the geostrophic wind, so that $\left|\frac{dV}{dt}\right| \approx \left|\frac{dv}{dt}\right|$, while the wind direction does not seem to diverge more than at the most 15° to the right from the geostrophic wind, whereas the divergence was calculated to be 30°.

Thus the horizontal acceleration effect cannot alone explain the low values of the wet-bulb potential temperature in Germany on the 22nd. We shall therefore check the humidity measurements. The humidity readings from Germany may, of course, in individual cases include errors of 20—30 %, but the values of the wet-bulb potential temperature at Norderney, Hamburg, Kiel and Swinemünde agree well with each other and we therefore assume that possible errors are small.

At Aldergrove the humidity figures are high (also at 1300 hours GMT). For the 700 mb. level at 0700 hours GMT the value is 79 %. The temperature is as high as — 3°, and therefore the lag errors cannot be great. However, we are forced to assume fortuitous errors amounting to as much as 20 %. If such an error is taken into consideration the wet-bulb potential temperature at Aldergrove is 10.5° as compared with 11.6° with a given relative humidity of 79 %. If, therefore, the air is so dry that the relative humidity only amounts to 59 %, a certain ascent may occur without precipitation, and we can draw a trajectory for the true wind which starts at the 700 mb. level and, after rising, ends in Central Germany at 600 mb., where the wet-bulb potential temperature has the same value, 10.5°. The wind's acceleration-deviation of approx. 15°, thus obtained, corresponds with the winds observed as well as with the calculations from equation (4), since the wind velocity decreases from 15 m. per sec. at Aldergrove to approx. 10 m. per sec. in Central Germany.

On the basis of the above discussion we can say that a powerful outflow of warm air has occurred from the low-pressure area towards the high-pressure area in the south in a layer starting at 2 km. and extending at least up to 5 km.

Near the centre of the low-pressure area an elevation of air occurs, which is shown by the rain which begins to fall at the south coast of Norway and in Northern Denmark. At the upper boundary of the warm-front at Kjeller the wet-bulb potential temperature is 6.5°, if we assume the air to be saturated. In reality the temperature at Kjeller is some degree too high, which appears from Table II and from the discussion in connection therewith (p. 10). If we take into consideration the systematical temperature-error, the value of the wet-bulb potential temperature becomes only 5.5°. This, then, is a value for air inside the warm-sector. It is very low, even lower than the value in the lower parts of the warm-sector below 1 gkm. at Aldergrove on the 21st. As the air at Kjeller does not give any precipitation and lies approx. 200 km. in front of the precipitation area, it seems improbable that the air has risen as far as from sea level. It is more probable that its vertical motion has been small and that it consequently has come from a region considerably north of Aldergrove, where the wet-bulb potential temperature, even at a high level, has had a value as low as 5.5°. It follows that the wet-bulb potential temperature would fall from Aldergrove to the possible front by 10.5°—5.5° = 5.0°. In the front and the district between this and Thorshavn, where the wet-bulb potential temperature is 3.1°, the fall would be 2.4°. The distance between a front at 700 mb. and Thorshavn must at all events be more than 200 km., and a fall in temperature within this distance of less than 2° is not reasonable considering the current and the difference of latitude. Therefore no isotherms remain which can be concentrated in the front, and

this supports our view that the front did not exist in the wave disturbance on the 21st., but was formed by the circulation. Neither were there, on the morning of the 21st., any distinct front hydrometeors; these began to appear later in the day.

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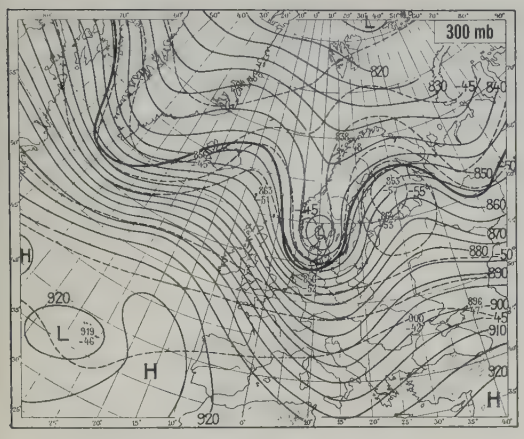
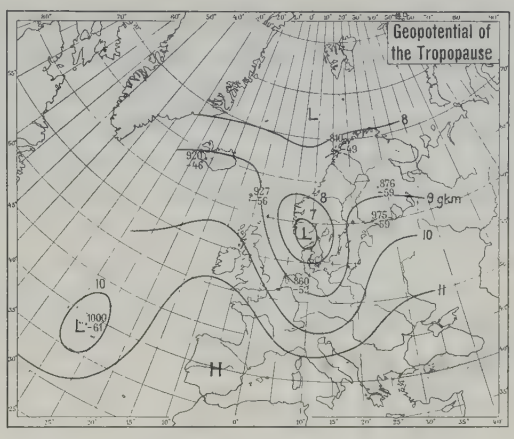
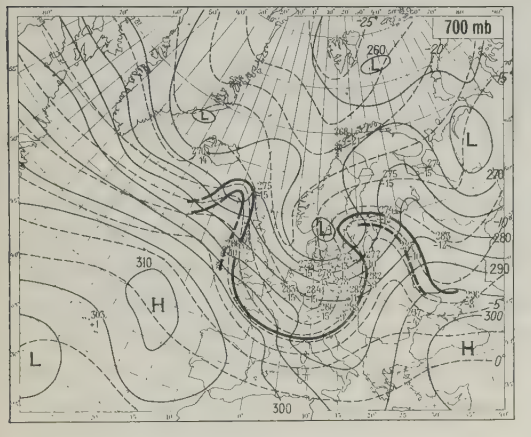
The sounding for Reykjavik on the 22nd. (Fig. 27) shows some strange discontinuities which must be discussed. At 1.2—2.5 gkm. there is a considerable warm-front which, to judge from the ground chart, would only be expected at a higher level, but there is no doubt that warm-air advection prevails low down in the troposphere. At 4.8—5.4 gkm. we find an isothermal layer with increasing humidity and a rise in temperature of roughly 5° in relation to the extrapolated temperature-height curve. A similar discontinuity is also found between 6.2 and 6.3 gkm., corresponding to a rise in temperature of approx. 2°. From 6.3 gkm. upwards the sounding curve has roughly the same course as the sounding from Carimaré at 40° N. The tropopause lies at almost exactly the same pressure level at both places, but Reykjavik is *warmer*, the absolute temperature being 2.5° higher and the potential temperature 1.5° higher. The potential temperature values in the sharp tropopause layers within the warm air do not as a rule reach higher values than approx. 325° in April at these northern latitudes (see Tab. VI, p. 69; compare also the discussion of Reykjavik's sounding on April 18th.). This potential temperature would correspond to an absolute temperature of approx. — 65° at the given pressure level. Other circumstances also throw doubt upon the correctness of the sounding. The 500 mb. chart has a reasonable appearance in the North-West Atlantic, but if we use Reykjavik's temperatures at higher levels we get an accumulation of isogeopotentials, which is improbable. In a narrow area between Thorshavn and Reykjavik gradient wind strengths would be obtained amounting to approx. 60 m. per sec., whereas the wind slightly south-west and north-east of this area would only be approx. 30 m. per sec. The fact that the extremely warm air cannot be found on the following day above England and France, where according to the trajectories it should be found, also supports the view that Reykjavik's temperature is too high in the upper troposphere on the 22nd. Without detailed knowledge of the instruments used and other conditions prevailing during the ascent, it is of course impossible to determine the character of the source of error with any accuracy. The following correction must therefore only be regarded as an attempt to bring the sounding into agreement with reality, at least in certain respects, and it is of course out of the question to use the soundings for making far-reaching conclusions. We assume that the two isothermal layers at 5.4 gkm. and 6.2 gkm. have been caused by errors in the temperature readings, and we have re-calculated the sounding from above 4.8 gkm. assuming that at the point 5.4 gkm. an error of 4.5°. has arisen, and that this error remains at higher levels, and at the point 6.2 gkm. increases to 6.0°. A sounding thus corrected has been inserted on Fig. 27 (dotted line) together with the uncorrected sounding. For height-charts and sections the uncorrected sounding has been used. Should the sounding be correct, which may possibly be determined with certainty in a future investigation, it must be marked as sensational, in view of the recorded



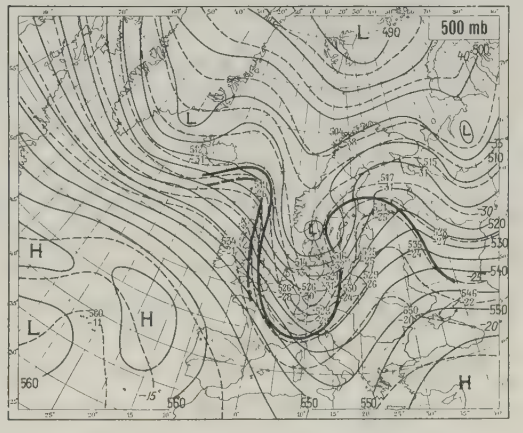

c) 300 mb.




d) the tropopause.




a) 700 mb.




b) 500 mb.

Fig. 39. Geopotential charts for April 23rd.

isothermal layers, all with a high humidity, lying above each other like a pile of warm-fronts, and also in view of the height and the temperature of the tropopause.

### April 23rd.

The cold-air mass which on the 19th. and 20th. was secluded from its origin in the north, and which on the 21st. could be studied with the aid of the sounding at Sevastopol, lay outside the district of observation on the 22nd. From the study of trajectories the conclusion could be drawn that at least a part of the mass lay south of the most southerly sounding station, Rostov, and it could also be assumed that, in the high-pressure area, with a rising pressure-tendency at that station, it would subside. On the 23rd., the rise in pressure has brought about that the high-pressure area gives the air current over the

Balkans and Turkey a component to the north (Fig. 39). Trajectories for 24 hours, which at 700 and 500 mb. (Fig. 43) end at Rostov on the morning of the 23rd., have their starting points at, or slightly to the west of, the Black Sea. If we assume that the cold-air mass actually lay above this region on the 22nd. and that its properties regarding wet-bulb potential temperature and mixing ratio were identical with the values of Sevastopol, we can calculate the vertical motion from the 21st. to the 23rd. within the cold-air mass.

*Table VII.*

| | Pressure mb. | $\Theta'$ | R | $x$ | P | $\Theta'$ | R | $x$ | P | $\Theta'$ | R | $x$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sevastopol, 21/4 0700 hrs. GMT .. | 847 | 4.0 | 80 | 2.5 | 535 | 6.0 | 73 | 0.6 | 390 | 10.3 | 73 | 0.35 |
| Rostov, 23/4 0700 hrs. GMT .. | 900 | 4.0 | 45 | 2.5 | 700 | 6.0 | 29 | 0.9 | 500 | 10.3 | 25 | 0.35 |
| Vertical descent .... | 500 m. | | | | 2 000 m. | | | | 1 500 m. | | | |

The values of wet-bulb potential temperature $\Theta'$, relative humidity R, and humidity mixing ratio $x$ in two air masses which may be regarded as identical. The calculated vertical descents are indicated in the bottom line of the table.

As can be seen from the above table, the correspondence of wet-bulb potential temperature and mixing ratio between Sevastopol and Rostov is excellent at 900 mb. and fairly good also at 700 mb. At 500 mb. it is more uncertain, as the values from Sevastopol have been extrapolated. The low values of the wet-bulb potential temperature at Rostov cannot, if we accept them, which it is reasonable to do, be explained in any other way than by supposing advection from the south of air belonging to the cold-air mass. The low values of the relative humidity show the intensity of the subsidence and its growth with increasing height. The air at 900 mb. has fallen approx. 500 m., at 700 mb. 2 000 m. and at 500 mb. possibly slightly less.

On the following day the cold air has completely vanished from the area of the chart. It may therefore be of value to recall its history. Behind a depression over Eastern Scandinavia and in front of a powerful high-pressure area, cold air was carried down over Central Europe and Western Russia on the 17th. At the beginning of its course it was slightly heated from below by a certain degree of shower activity, in the course of which it simultaneously absorbed some humidity. After pouring down through Southern Russia, it became practically stationary, and on the 19th. and 20th. was secluded from its origin by warm air, which at 55° N moved with a great speed to the east. Up to the 21st. the stationary air was only subjected to slight changes, but after that subsidence occurred which caused an adiabatic heating. The downward motion (and also to a certain extent the increase in pressure, which has the same effect but less pronounced), occasioned an increase in the wet-bulb potential temperature at fixed pressure levels, but it is worth pointing out that the air has hardly undergone any non-adiabatic changes. The assimi-

lation of heat by radiation or turbulent mixing has not commenced to any noticeable degree, and the transformation from polar air into an air mass characteristic of the latitude, the position and the season is apparently slow. The resistance to the surroundings can to a certain extent be explained by the pressure distribution and the vertical extension of the air masses which included the whole troposphere, on account of which the depression at ground level increased with the height and counteracted subsidence. In principle the transformation of warm air (**T**) to cold air (**P**), which occurs in a cyclone during an occlusion process, corresponds to a transformation of cold air (**P**) to warm air (**T**) in an anticyclone. The observed phenomenon clearly shows that the transformation of the air must not always be regarded as a rapid process, cf Douglas (1925) and (1935), and also that the previous history of an air mass must be known if, without any kind of aerological observations, we are to gain an understanding of its physical state. As a rule an accurate estimation of the physical state is impossible without direct aerological observations.

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The depression over Scandinavia has deepened still more since the previous day, and at its centre near Gothenburg has a pressure of 978 mb. (Fig. 13 p. 37). The circulation is powerful. Wind strengths of 9 Beaufort are reported at 0700 hours GMT from several places such as the island of List and the southern point of Öland. During the night the wind strength at Elbe lightship I has amounted to 11 Beaufort. The cold air to the west of the low has moved right down to the Alps. At ground level a fairly well developed cold-front in the south, with showers and thunder, can be found. To the north the front is less distinct, but still noticeable in the temperature field. The warm-front, on the other hand, is easier to find in the north, in connection with the precipitation area, than in the south, where the temperatures only give certain indications of the position of the front. The aerological observations give a good illustration in the height-charts of how the warm-air tongue from the west is attacked by the violent inburst of cold air. If we attempt to draw a picture of the fronts at high levels, we get an indistinct one. The reader is referred to the temperature-height diagrams (Figs. 40 and 41), which we wish to discuss with respect to some stations with such positions in the proximity of the ground fronts that the ascents may be expected to pass through the front-surfaces at high levels. See also Fig. 42.

At *Smolensk* there is an inversion with slightly decreasing humidity at 2.3—2.6 gkm. The value of the wet-bulb potential temperature is not higher than 5.5° at the upper level of the inversion, which appears to be unreasonably low for the warm-front, if we bear in mind the fact that the value at Kjeller, 800 km. further to the north, was roughly the same on the 22nd. It is more probable that the inversion is a faint subsidence inversion in the cold air within the outer regions of the high-pressure area. In the layer 2.6—4.0 gkm. the lapse rate in Smolensk is rather small, and there may be a frontal zone. The humidity is not recorded at 4.0 gkm. and the wet-bulb potential temperature must be less than 9.2° at this point.

There is no front to be found at *Moscow*. The absence of a warm-front at high levels is in full agreement with the conditions in the eastern parts of the cyclone on the previous day.

At *Warsaw* there is a disturbance in the height-temperature curve between 2 400 and 3 000 gm., in which the temperature falls from — 8.5° to — 9.2°. At the lower level

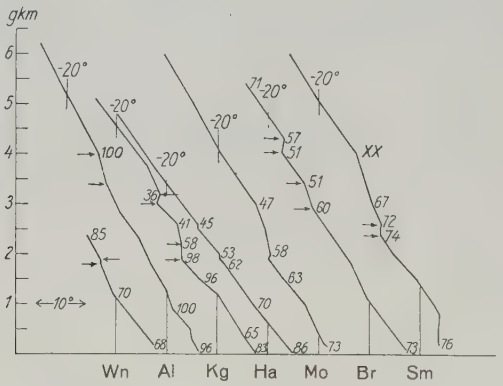


Fig. 40. Some temperature-height diagrams on April 23rd.
Vienna, Aldergrove, Königsberg, Hamburg, Moscow, Breslau and Smolensk.

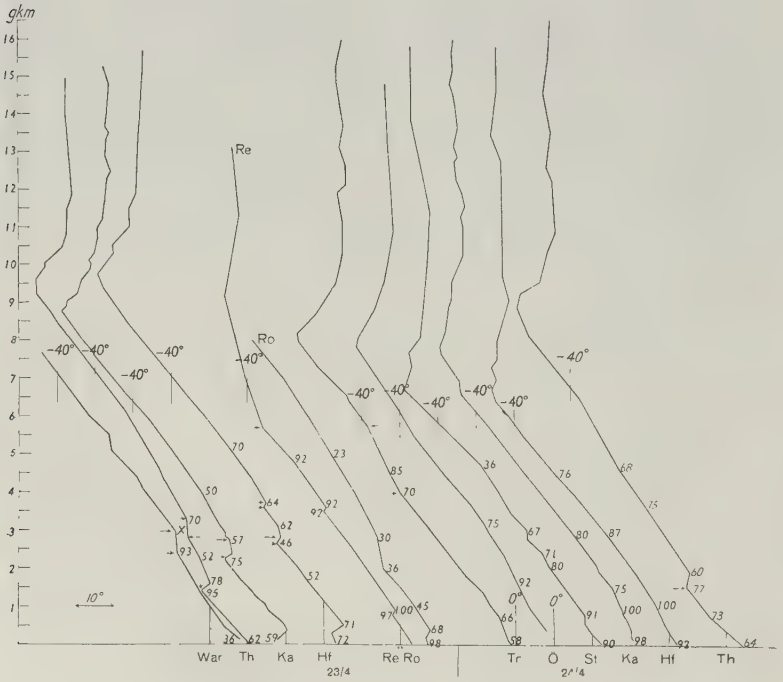


Fig. 41. Some soundings on 23.—24th. April 1939. Warsaw, Thorshavn, Kajana, Helsingfors, Reykjavik, Rostov — Tromsö, Östersund, Stockholm, Kajana, Helsingfors, Thorshavn.

the relative humidity is 93 %, but at the higher one it has not been recorded. The wet-bulb potential temperatures are 5.9° and < 8.4°. Warsaw lies very close to the ground cold-front, and the disturbance aloft must presumably be regarded as a consequence of subsidence in the outer parts of the high-pressure area. It may, however, be possible that it is the cold-front, which has a large inclination near the intersection with the ground.

An isothermal layer, which might possibly be the cold-front, has at *Vienna* a height of approx. 1 900 gm., and the value of the wet-bulb potential temperature is 7.5°. Close above this the sounding is cut off. At *Breslau* the lapse rate is very faint between 2 900 and 3 400 gm., the relative humidity decreases within the layer and at the upper level the wet-bulb potential temperature is 6.0°. A small inversion with increasing humidity, bounded at the top by a layer of As translucidus, is to be found at 4 300 gm. At the upper boundary the wet-bulb potential temperature is 10.0°.

At *Königsberg* the gradient between 1 900 and 2 200 gm. is very small; the temperature falls 0.3° in 300 gm. simultaneously as the humidity decreases from 98 to 58 %. Between 3 000 and 3 200 gm. there is a small inversion from — 12.2° to — 11.5° with decreasing humidity from 41 % to 36 %. The wet-bulb potential temperatures at the upper levels of the layers are 4.2° and 6.1° respectively.

Which of the disturbances in the sounding curves for Vienna, Breslau and Königsberg is now to be interpreted as a cold-front? On the 22nd. the value of the wet-bulb potential temperature could not be measured in the front, but at 700 mb. it must lie between the values 4.1° at Mildenhall and 7.5° at Soesterberg and, correspondingly, at 500 mb. between 5.8° and 9.4°. The value of the wet-bulb potential temperature for Vienna, 7.5°, is thus compatible with the interpretation of the cold-front. The calculated trajectory also supports the view that the thin isothermal layer is identical with the cold-front of the previous day (see Fig. 43 b). In Breslau at 500 mb. (Fig. 43 c) the trajectory comes from a district west of Aldergrove where the wet-bulb potential temperature on the previous day was approx. 10°, and this must be regarded as a kind of transitional air mass or perhaps a warm-air mass. The lower air must be referred to the cold air, and then the inversion with decreasing humidity at approx. 3.1 gkm. is a subsidence inversion, whereas the upper inversion, despite the high value of the wet-bulb potential temperature, may be interpreted as a cold-front. At Königsberg the lower inversion must undoubtedly be regarded as a subsidence inversion, while the second inversion appears also to lie within the cold air. If we take the trajectory for 24 hours, which at 700 mb. ends at Königsberg, we find its origin west of Scotland, and the value of the wet-bulb potential temperature at Königsberg, 5.5°, corresponds well with the value on the previous day at the starting point, if we reckon with a downward motion of approx. 500 m. At great heights also the air at Königsberg seems to consist of cold air. It is true that the value of the wet-bulb potential temperature rises with the height, reaching at 5 gkm. the value 8.6°, but this value is combined with low values for relative humidity and mixing ratio. It is clearly a question of subsided air, and the subsidence can be estimated to be about 1 km., if we assume that at the starting point of the trajectory 24 hours earlier

the air had a relative humidity of approx. 70 %. According to Namias (1934 A) such a subsidence is of normal size. The value 8.6° could thus have been measured in the original air mass at 6 gkm., and for this level the value is far from characteristic of warm air. Compare the values of the wet-bulb potential temperature on the 23rd. at Aldergrove, over 10.5°, at Smolensk, 10.2°, and even at Moscow, 9.0°. The trajectory for 500 mb. also starts west of Scotland within a district which must belong to the cold-air region, the wet-bulb potential temperature of which corresponds to that of Königsberg, if the downward motion is taken into consideration.

As we see, it is far from easy to find the fronts which are assumed to limit the warm-sector. If they have previously existed at all they have partly or completely vanished, while other disturbances in the sounding curves have occurred, of which several certainly have nothing in common with the previous fronts.

We shall now attempt to investigate the frontal conditions further to the north. The ground observations show quite good agreement with Bergeron's pattern for an occluded cyclone in Chromow's version (1940), in the case when the cold air in the rear of the cyclone is warmer than that before it. This means, according to Bergeron, that an area of continuous precipitation from upward gliding air occurs there, limited to the south by the upper cold-front, and also, between the upper cold-front and the ground warm-front, a district with drizzle or intermittent light sleet and finally, to the south of the warm-front, a district of instability showers.

April 23rd. was a Sunday, the International Aerological Week was over and height observations were limited. In Sweden and Southern Norway, which were especially favourably situated for investigating the cyclone, no soundings were made, which is greatly to be regretted. The only aerological material from within the cyclone is obtained from the previously mentioned cross-sections drawn by the Swedish Airlines flying staff on the routes Stockholm—Malmö and Stockholm—Berlin. From these, two results can be obtained. Firstly the temperature at 1230 hours GMT at the 700 mb. level at 16° E and 58° N is — 11°, or, corrected according to the indications on p. 12, — 13°, and at 17° E 59° N corrected — 12°, which values can be used in drawing isotherms at this level. Secondly, sections for the 22nd. at 1600 hours GMT in the same district show that a bank of As-clouds lay at a height of 2 500—2 800 gm., which we associate with the upward motion and the formation of precipitation which was observed from the ground. We will return to the consideration of this bank of clouds later, but first let us discuss the soundings from Helsingfors and Kajana. At Helsingfors (Fig. 41) two small inversions are found at 2.6—3.1 gkm. and at 3.6—3.7 gkm. We interpret the upper limit of the latter inversion as the lower limit of the warm air. The relative humidity increases from the lower boundary of the lower inversion, where it has the value of 46 % to 64 % at the lower boundary of the warm air. The wet-bulb potential temperature is calculated to be 7.5° at this point. The trajectory for 700 mb. (Fig. 43 b) began on the previous day within the warm air in the district between Amsterdam and Hamburg. It runs over Western Latvia, where no precipitation has occurred during the last 24 hours. A certain upward motion may, however, have occurred, as the air at Soesterberg was comparatively

dry with a relative humidity less than 50 %, whereas that at Helsingfors is moist and cloudy. The value of the wet-bulb potential temperature fits in well, as does the mixing ratio, if we calculate with a relative humidity of 64 %. It is, however, probable that the relative humidity is greater, at least corresponding to saturation with respect to ice. The consequence of this would be that the mixing ratio had increased during the day and night, which may possibly be explained by the fact that precipitation has fallen and evaporated in the layer, which has thereby become moist. At 500 mb. the air should, according to the trajectory, have come from the district to the west of Soesterberg on the 22nd., and the upward motion appears to have been insignificant. The tropopause lies at a high level and is cold and sharp, and the potential temperature has the high value of 319°, as in a normal tropical air mass. At Kajana (Fig. 41) there is an inversion at 2.3—2.8 gkm., but this is associated with a decrease of humidity from 70 % to 59 % and must be regarded as a subsidence inversion. The upper troposphere is relatively cold, but the tropopause is fairly high and cold, no doubt owing to its position in the high-pressure ridge over Eastern Finland. The potential temperature of the tropopause, 313°, is approx. 11° lower than at Helsingfors, and thus the tropopause at Kajana cannot be identical with that at Helsingfors.

A study of the trajectories shows, in addition to what has already been mentioned, the following facts which may be of interest (see Fig. 43). The trajectory ending at Stockholm at 700 mb. comes from a point 2° W 54° N, and should thus consist of cold air. At 500 mb. the corresponding trajectory comes from 7° W 55° N and should thus also be referred to the cold air. From a point north of the warm-front at Kjeller the trajectory runs at 700 mb. to Kajana. The wet-bulb potential temperature is correct without assuming any vertical motion. At 500 mb. the corresponding point is 100 km. to the west of Kjeller. The wet-bulb potential temperature at Kajana is 6.0° in contrast to about 7.0° to the west of Kjeller. We may imagine an upward motion of approx. 1 km. which causes the formation of clouds but not precipitation, or a certain outflow at high levels from the low-pressure area.

A trajectory from the north-western part of the warm-sector at 700 mb. runs in a spiral around the centre of the cyclone, while this moves to the east. In the first section of the trajectory the air must rise considerably and precipitate a large amount of water. The trajectory appears to end somewhere in North-Western Germany. Of the trajectories to the precipitation area in Central Sweden on the 23rd. (point 13° E 60° N) that at 700 mb. comes from 1° E 53° N and that at 500 mb. from 5° W 60° N, thus both starting in the cold air district on the 22nd.

The calculated trajectories should be regarded as fairly uncertain in view of the movement of the cyclone and the possible existence of wind strengths which deviate from the gradient wind force in connection with pressure variations, and wind directions deviating from the gradient wind in connection with acceleration or retardation effects. Combined with the study of wet-bulb potential temperature and the mixing ratio, that of the trajectories should, however, make possible some reliable results.

During the sounding at 0530 hours GMT Helsingfors lay about 175 km. in advance of

the upper cold-front. The height of this front is not known. With a distance of approx. 300 km. from the occlusion point its height before Helsingfors must be 1.5—3.0 km., corresponding to a frontal inclination of 1/200 to 1/100. If we assume that the height is 2.5 km., this corresponds to an inclination of 2.5/300, and then the inclination towards Helsingfors of the warm-front from the upper cold-front will be (3.7—2.5)/175 or 1/145, which is reasonable. If we also assume the same inclination of the upper cold-front nearer the centre of the cyclone, we find that it reaches the tropopause and enters the stratosphere long before the centre is reached. This absurdity can be avoided if we assume a smaller inclination of the front in the central part of the cyclone. The question is, however, whether such an assumption is justified. The amount of precipitation, which is very small in the outer parts of the depression, amounts in the central parts to, for example, 16 mm. at Ferder and 8 mm. at Karlstad between the 22nd. at 1800 hours GMT and the 23rd. at 0700 hours GMT, which shows how much greater the ascent must have been in this district. A rough calculation leads to the conclusion that the upward motion near the centre was eight times greater than that near Helsingfors.

As mentioned above, reports from an aeroplane on the evening of the 23rd. in the immediate vicinity of the warm-front's precipitation area showed that the clouds were of the type As with an upper level of 2 500—2 800 gm. There is now reason to suppose that the precipitation on the 23rd. was not formed at levels appreciably higher than these. The air at these high levels is so cold and the absolute humidity so small that a great vertical motion must occur, even giving rise to the precipitation termed as »moderate snowfall» (cf. the calculations for the cyclone on the 24th.). We conclude that the snowfall was formed in lower layers. Trajectories at 700 and 500 mb. show that the air above the precipitation area at these levels was also part of the cold air above the North Sea on the previous day. Thus we find that it is a part of the original cold air which in the present period of the cyclone causes, in the course of its elevation, the continuous precipitation in the central parts. For what reason, however, does the cold air rise? After the original warm air at the north-western point of the warm-sector has been elevated and flowed out at a high level from the cyclone, the cold air which displaced the warm air appears in its turn as warm air in relation to the following cold air, the temperature of which, as the height-charts show, falls successively. When the depression has been formed and any fronts have been disintegrated by vertical motions, there is no fundamental difference between the elevations in these two cases. An air mass is displaced by a following colder air mass, and the temperature difference is roughly the same in each case. We might speak of a regeneration of the cyclone, as in the cases described by Schröder (1929) and Palmén (1929), but this is a continuous regeneration independent of fronts. The interpretation of the fronts within the depression as occluded remains of previous warm- and cold-fronts is obviously incorrect in this case, but the actual phenomenon, shown on the chart, of one district of continuous precipitation, another of drizzle and a third of showers, is rather clear. It is possible that fronts are formed successively in the lower layers. Another possibility is that the distribution of precipitation is a resultant of the pressure distribution, of the frontless distribution of temperature and hu-

midity in the depression and of vertical motions caused by these factors, and that thus the comparatively sharp transition between the various zones is more complicated. A sharp boundary of the precipitation area is also to be found in its northern parts without any front existing there. Future investigations of occluded cyclones, made without assuming any special conditions, with better aerological data, should clarify such obscure questions as these, and also determine to what extent the present results may be given general application.

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The soundings from Thorshavn and Aldergrove support the assumptions made regarding the sounding of the previous day at Reykjavik. The high temperature values above 500 mb. at Reykjavik given in the observation telegrams cannot be made to agree with the values in the warm-sector on the 23rd. The value of the potential temperature in the tropopause at Reykjavik on the 22nd. amounted to 333.5° (see Table VI, p. 69) in the uncorrected sounding; at Thorshavn on the 23rd. the value was 317.1° and near the cyclone at Hamburg 315.0°. The corrected sounding for Reykjavik on the 22nd. gives the value 324.3° for the potential temperature in the tropopause, which corresponds well with the values obtained from the 18th. to the 20th. April within **T**.

At Thorshavn (Fig. 41) there is a sharp inversion at 1 200 gm. above a layer of air which has been rendered moist-indifferent by flowing to the south above relatively warm water in the rear of the cyclone over Scandinavia. Above it there is a fairly dry and cold air mass which has come most recently from the south-west or west. At 2.8—3.3 gkm. there is an almost isothermal layer with increasing humidity, which we regard as the warm-front in the Icelandic cyclone. The precipitation area has still not reached Thorshavn an hour after the sounding, i. e. at 0700 hours GMT, when the front surface must lie roughly 0.5 gkm. lower or at approx. 2.5 gkm. At Aldergrove (Fig. 42), on the other hand, where the front appears to lie between 3.5 and 4.1 gkm., rain falls at 0700 hours GMT. The cold-front to the same cyclone cannot be analysed either with the aid of ground observations or with height-observations, and its position is therefore very approximate. At Reykjavik (Fig. 41) we see at 5.7 gkm. a low newly formed tropopause. The station lies very near the centre, even to the north of the occlusion front, but the whole sounding indicates typical cold air (**P**). The rain which falls near the ground front here must have been formed by an ascent of cold air, just as in Scandinavia.

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Charts have been drawn to show the changes in pressure during the last 24 hours at various levels. Instead of the changes of pressure at standard heights, the changes of geopotential $\Delta\Phi$ have been calculated at the levels 1 000, 700, 500, and 300 mb., which can easily be recalculated into pressure variations $\Delta p$ for a fixed geopotential level.

According to Exner (1913) the change of pressure $\Delta p$ at a certain level $z$ with the pressure $p$ may be expressed as a function of the change of pressure at ground level $\Delta p_0$, where the pressure is $p_0$, of $T_m$, the mean temperature in the layer $p_0$—$p$, and of $\Delta T_m$, the change in $T_m$.

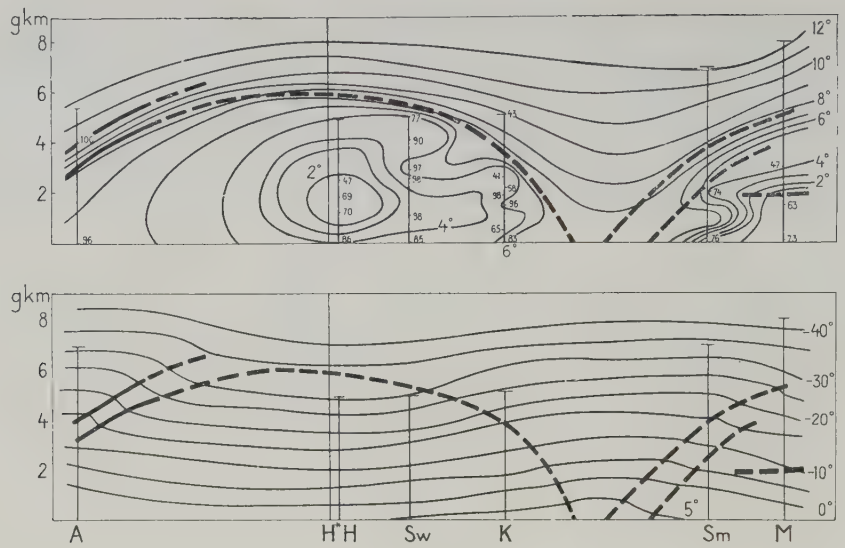



Fig. 42. Vertical sections showing the temperature (C) and the wet-bulb potential temperature on April 23rd. Aldergrove, Hamburg (radio-sonde), Hamburg (aeroplane), Swinemünde, Königsberg, Smolensk and Moscow.

$$\Delta p_0 = \frac{p_0}{p}\Delta p - \frac{gz\,p_0\,\Delta T_m}{RT_m{}^2}$$

If no change occurs in the mean temperature:

$$\Delta p = \frac{p \cdot \Delta p_0}{p_0}$$

$$\text{whence } \Delta\Phi = \frac{\Delta p_0 \cdot RT}{p_0}$$

$\Delta\Phi$ would then decrease with height to the same extent as the temperature. Actually $\Delta\Phi$ increases with height despite the decreasing temperature, and at 300 mb. is roughly 75 % greater than at ground level. This is due to the fact that $\Delta T_m$ is associated with $\Delta p$.

W. H. Dines (1912) calculated the correlation coefficient between the pressure at 9 000 m. and the mean temperature in a layer of air between the ground and 9 000 m. to be 0.92. Hence we see that an increase of pressure at 9 km. is intimately connected with a rise of the mean temperature in the troposphere. Hesselberg (1915) showed that this change of temperature could be explained by adiabatic heating of downward currents of air which carried down potentially warmer air from higher regions. Since then a large number of works have been published regarding the connection between the changes in pressure and the temperature. Of these works will be mentioned only those of Rossby (1928), who established formulae for calculating the connection between frontless advections and changes in pressure, and Ertel (1931, 1936, 1937 and 1938) who in his theory

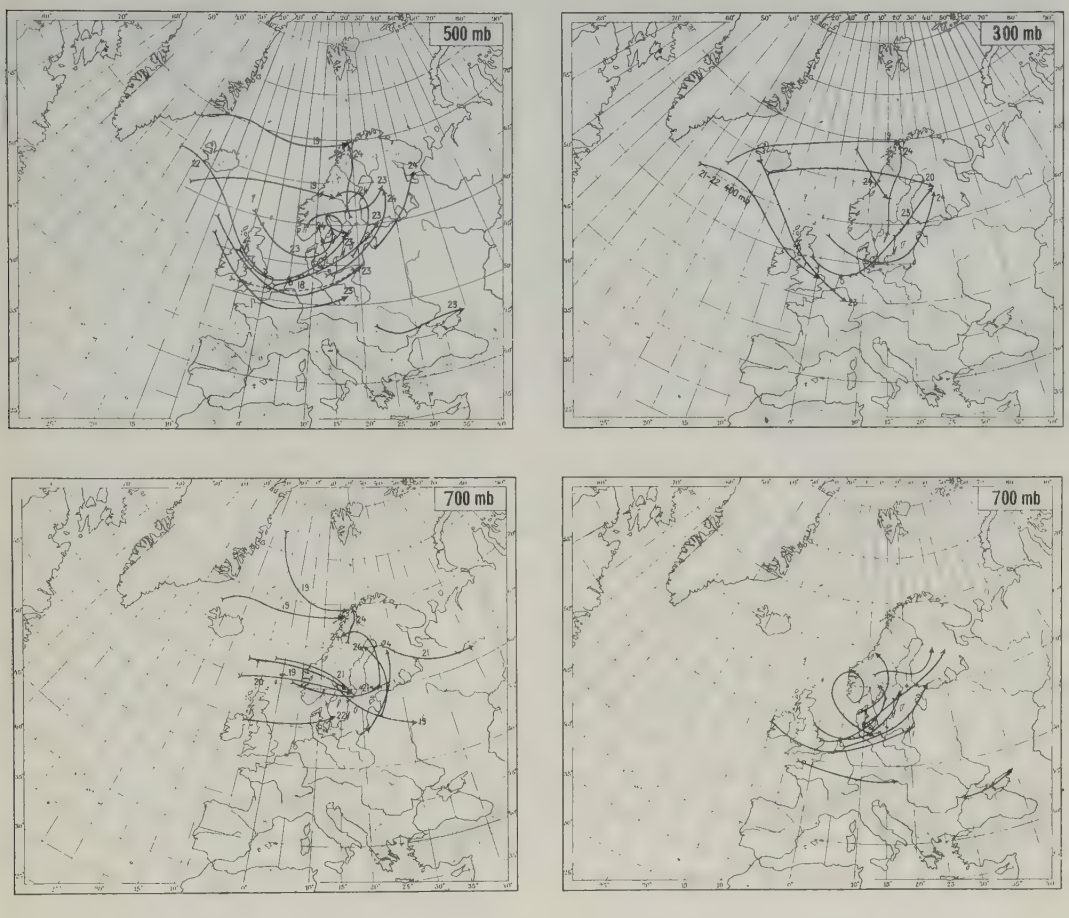
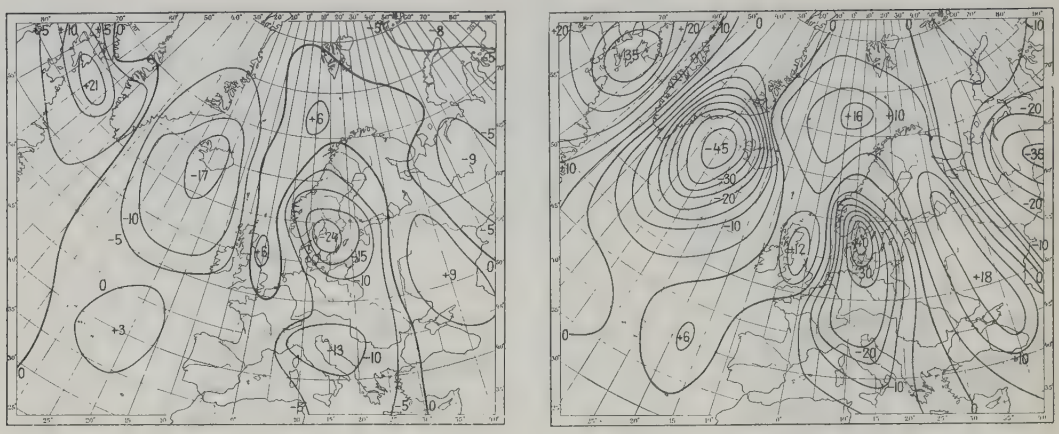



Fig. 43. Gradient wind trajectories for times 0700 hrs.—0700 hrs. GMT at (a) 700 mb. (b) 700 mb. (c) 500 mb. and (d) 300 mb. In (a), (c) and (d) the time is given for the end of the trajectory by means of a date. In (b) all trajectories refer to 0700 hrs. GMT 22/4 to 0700 hrs. 23/4.

of singular advection has indicated sloping discontinuity surfaces, especially in the tropopause level as a source of changes in pressure.

According to W. H. Dines (1912 and 1919) there is a distinct connection between the pressure at ground level and the pressure at a height of 9 km. The correlation factor is, according to Dines, as large as 0.68. One would expect that the changes of pressure at ground level and at 9 km. would have a phase difference in relation to each other and that the phase would be so small that the correlation would remain at the calculated value of 0.68. Such a phase difference was first determined synoptically by Douglas (1921) and statistically by Schedler (1921). Several serial ascents have been investigated by J. Bjerknes and E. Palmén (1937), J. Van Mieghem and L. Dufour (1942) and others, who have arrived at the result that the phase difference 0—9 km. has amounted to

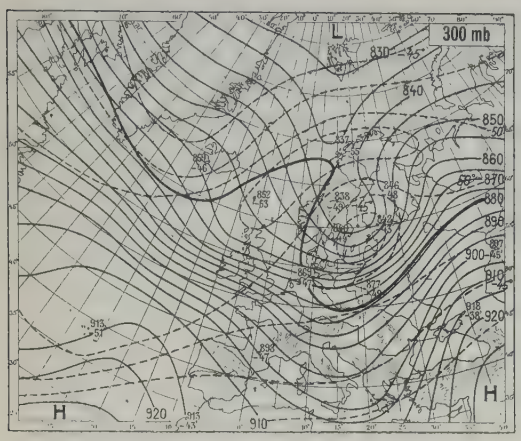


a) 1000 mb. b) 300 mb.

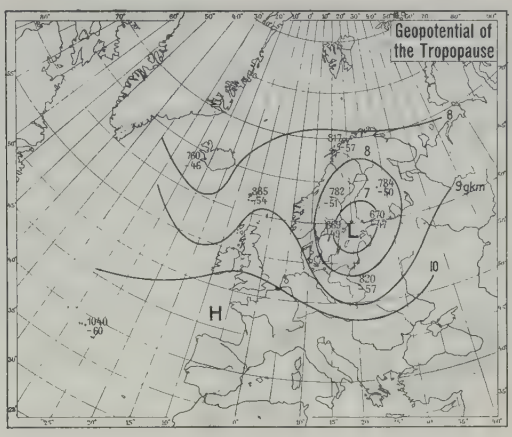
Fig. 44. The difference in geopotential between charts for April 23rd. and 22nd. showing the isoallobaric regions.

—5 hours. Our isallobar-charts for 24 hours show a similar phase difference. The relatively coarse network of observations, however, makes an exact calculation of its size difficult.

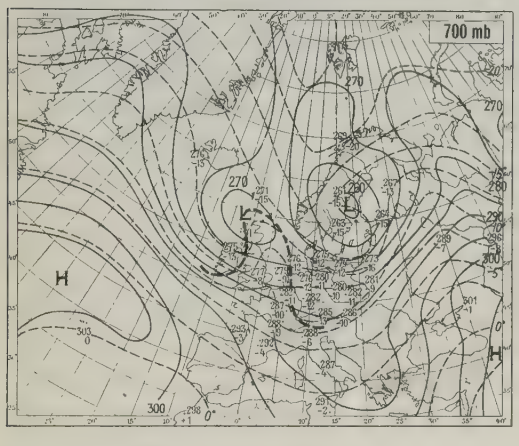
In a cyclogenesis air flows out from the cyclone at certain levels and the depression caused thereby is shown on the isallobaric charts as a region with a falling tendency, (Fig. 44). The outflowing air must of course move into other districts and there cause a rising tendency. Around the pole there is a series of alternating rise and fall areas, which as a rule move eastward. If the cyclogenesis were a simple reversal phenomenon in accordance with Margule's scheme, the fall-area would completely correspond to a rise-area in its immediate proximity. We have calculated the sizes of the rise- and fall-areas as the volumes which are obtained if the surface of an area is multiplied by the mean geopotential difference. On the 23rd. the isallobaric charts show that the pressure has fallen over South Scandinavia and Central Europe during the last 24 hours. The fall-area is widespread and deep and is not nearly compensated by the subsequent rise-area. Not even if we add the volumes of the preceding and the subsequent rises of pressure, does this amount to the volume of the fall. This shows the direct connection between the cyclone and the pressure conditions, and thus also the connection between the weather and pressure conditions, at very considerable distances, certainly exceeding 2 000 km., from the centre. A direct effect of the cyclogenesis may be a reversal at other places, so that the indirect effect becomes impossible to survey. Future synoptical aerology must be based on a world-wide aerological network if it is to determine the wide relationships between the factors influencing the weather. For the practical weather service aerological circumpolar charts will no doubt soon provide an important aid.



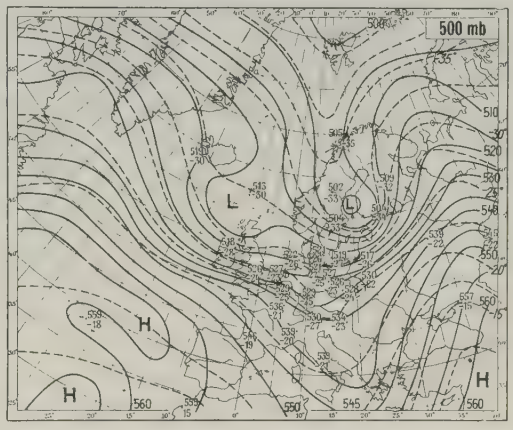

c) 300 mb.




d) the tropopause.




a) 700 mb.




b) 500 mb.

Fig. 45. Geopotential charts for April 24th.

**April 24th.**

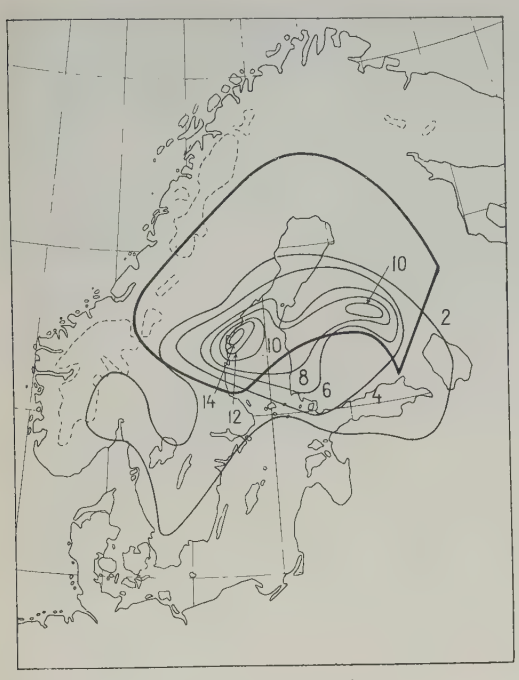
The high-pressure area over Eastern Russia has increased and become strengthened (Fig. 14, p. 38). To its western side warm air is conveyed from the south. As we see from a widespread layer of As-clouds, the air is rising, and near a depression over Greece there is a well developed precipitation area. Somewhat further to the north there is a faint advection of slightly colder air, and at ground level a fairly distinct cold-front may be seen.

The deep low-pressure area over Scandinavia now has its centre over the Gulf of Bothnia. It is being filled out, but the pressure is still as low as 982 mb., as contrasted with 978 mb. on the 23rd. As on the previous day the front-patterns of the occluded cyclone can be inserted, but it is equally clear that the air above the upper cold-front indicated is not identical with that of the warm-sector two days earlier.

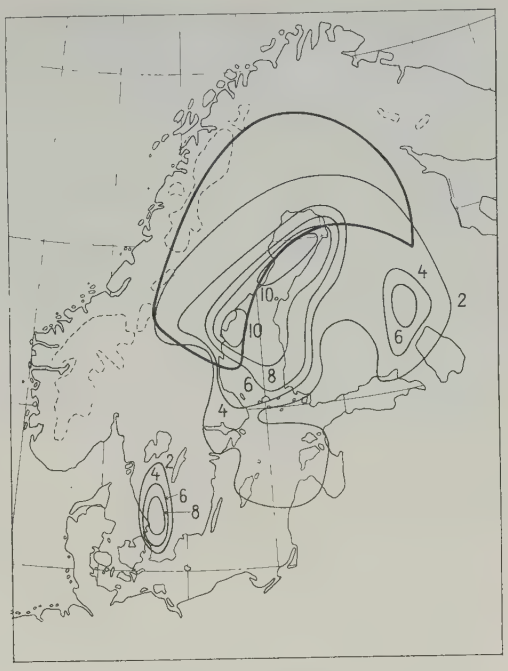
As before we try to follow the course of the air during the last 24 hours. Some trajectories for 700 and 500 mb. have been drawn in Fig. 43. They show that the air of Kajana at 700 mb. comes from Northern Germany without appreciable vertical movement. The air of Kajana at 500 mb. comes from 54° N 12° E and thus also is cold air. The trajectory at 700 mb. from the centre of the warm air tongue north-east of Königsberg at 56° N 25° E ends at a point at 65° N on the coast of Norrland (Sweden). However, the air has probably not followed this course, but in an upward motion veered to the right (compare the 500 and 700 mb. charts, Fig. 45). There is probably also a retardation — deviation to the right in this region. From the trajectories and the values of the wet-bulb potential temperatures we see that at the 700 mb. level the air near the centre of the cyclone lay outside the warm-sector on the 22nd. At 500 mb. this must also be the case. It is true that the trajectory at 500 mb., ending at Östersund on the 23rd., started in a region which may have lain within the warm-sector, but the air must have been rising rapidly at the time and been deflected to the right. The air at Östersund at 500 mb. is not warm air. The wet-bulb potential temperature is less than 4.5°. The trajectory at 300 mb. at Östersund also indicates that the air there was originally cold air, although a moderate upward motion has occurred below the tropopause. This is fairly high, and is cold and sharp. The same is true of the lower layers at Tromsö. There also the trajectory at 500 mb. started within the limits of the warm air on the 23rd., but a powerful upward motion must have occurred. The air must then have veered to the right. The upward motion, which is distinctly shown by the relatively high and cold tropopause at Tromsö, has reached up to about 8 gkm. At Kajana the air up to the maximum height is clearly cold air. At Tromsö (Fig. 41) there is, between 4.0 and 5.8 gkm., a frontal zone which may be regarded as the remains of the previous warm-front. The evidence against this is provided by the fact that the »warm air» above the frontal zone at Tromsö is colder at all levels than the cold air at Kajana. It is thus our view that the frontal zone at Tromsö has nothing in common with the previous warm-front, but has a different origin. With these assumptions it is clear that the precipitation in Northern Sweden and Finland comes entirely from air which at the earlier stage of the cyclone was regarded as cold air. If, however, we again take the less probable view that the air above 500 mb. over the precipitation area is made up of originally warm air, it is nevertheless clear that the larger part of the precipitation is formed in cold air.

The humidity which may be condensed during an elevation of the air above 500 mb., if the temperature is — 32° or lower, is not sufficiently large for the precipitation to be called moderate snowfall. The complete amount of water condensed would give a precipitation of 0.5 mm., which is small compared with the amount that actually falls. We have calculated the humidity that originally was to be found in that part of the warm sector which took part in the upward motion (elevation), and also the precipitation formed by »upward gliding» in the cyclone.

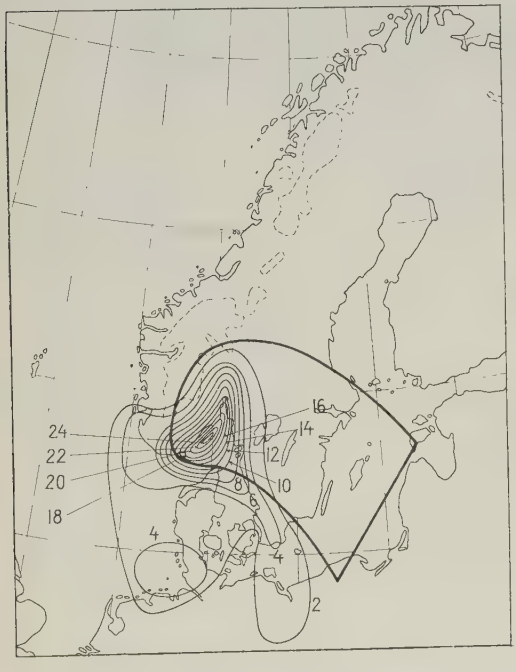
First we calculate the amount of precipitation in connection with an upward gliding motion from the 22nd. at 0700 hours GMT to the 24th. at 0700 hours GMT. Precipitation charts have been drawn for 1800 hours GMT on the 22nd., 0700 and 1800 hours GMT



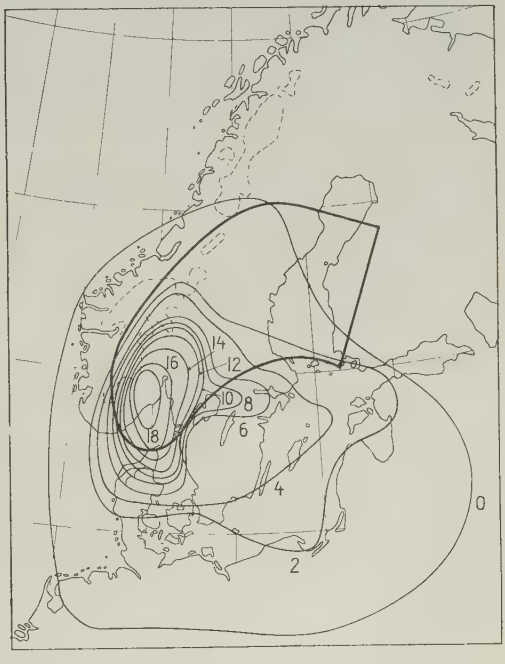

c) 1800 hrs. GMT. $^{23}/_{4}$.




d) 0700 hrs. GMT. $^{21}/_{4}$.




a) 1800 hrs. GMT. $^{22}/_{4}$.




b) 0700 hrs. GMT. $^{23}/_{4}$.

Fig. 46. The quantities of precipitation measured during the observation periods. The area inside the heavy line indicates the precipitation originating exclusively in upward gliding motion or elevation.

on the 23rd., and 0700 hours GMT on the 24th. (Fig. 46). In calculating the precipitation the stations have been included where readings have been made at 0700 hours GMT as well as at 1800 hours GMT. Consideration has also been taken of reports obtained from the precipitation stations of the 3rd. class of the Meteorological-Hydrological Institute of Sweden. At these stations, which number about 700, precipitation readings are only made at 0700 hours GMT, but as several stations definitely lie within areas which have had no precipitation during one-half of the 24 hour period, their observations have been readily employable in drawing charts for the other half of the period. It has also been ensured that the sum of the precipitations on the charts at 1800 hours and 0700 hours GMT consistently agrees with the observations at 0700 hours made at the 3rd. class stations. In calculating precipitation from upward gliding air, to start with only the area within which precipitation exclusively of this kind has fallen has been included in each period of observation. Thus a part of the precipitation of this kind has not been included in this calculation as, within large districts, there has been precipitation formed by upslope motion as well as showers between two observation periods. These districts have been excluded, as the proportion between the different kinds of precipitation is not at once apparent. The consequence of this is that in the calculation we obtain a smaller amount of precipitation than that which has actually occurred. The amount calculated in this way totals $576 \cdot 10^{13}$ g.

Precipitation registrations from a few places in the south of Sweden, such as Svalöv, Ölvingstorp, Vinga, Stockholm and Åsaborg, definitely show that a large proportion of the precipitation measured on the 23rd. at 0700 hours GMT at these places (calculated as on the average 70 %) certainly occurred in connection with the passage of the warm-front. They also show that probably 15—30 % more fell immediately after the cold-front, also from the warm air. If 70 % of the amount measured at 0700 hours GMT on the 23rd. in Sweden south of the position of the upper cold-front at 0700 hours GMT is included in the calculation of the amount of precipitation from warm air, an additional amount totalling $90 \cdot 10^{13}$ g. is obtained. If we assume that the same proportion holds for the precipitation as far as 300 km. south of the upper cold-front in Finland on the 23rd. at 1800 hours GMT and on the 24th at 0700 hours GMT, $102 \cdot 10^{13}$ g. more is obtained. According to these calculations the total amount of precipitation from the warm air amounts to $768 \cdot 10^{13}$ g.

The total quantity of water vapour in a vertical pillar with a base area of 1 cm², calculated up to the level $z$, is obtained from the expression $\int_0^z \varrho_v dz$ if $\varrho_v$ is the density of the vapour. As we are dealing with the elevation of air we have assumed that the air is saturated and that the temperature follows a moist-adiabatic. The variation of $\varrho_v$ is then so complicated (Brunt, 1934) that the integral is most easily solved by graphical integration.

The density of water vapour in saturated air, $\varrho_v$, is $= \frac{5}{8} \frac{e}{RT}$, where $e$ is the pressure of water vapour in saturated air at the absolute temperature $T$ and $R$ the gas constant

appropiate to dry air. $R$ has the value $2.8703 \cdot 10^6$ in C.G.S. units and the value $2.8703 \cdot 10^3$ if $e$ is given in millibars, $\varrho_v$ in $g$ per $cm^3$ and $T$ in degrees Kelvin. The value of $e$ is obtained e. g. from Brunt, (1934). In a system of co-ordinates (Fig. 47 A) the values of $\varrho_v$ corresponding to certain heights are plotted, a curve $A$ is drawn and by integration $\int_0^z \varrho_v dz$ is obtained. Such a calculation for the moist-adiabatic that at 1 000 mb. has the value + 8°, gives the result that the total quantity of water amounts to 1.8 g. per $cm.^2$

We assume that the air is consistently elevated by 1 gkm. In this elevation it is cooled along a moist-adiabatic, and water is condensed. From the adiabatic paper temperature and pressure values after elevation are obtained. The increase in volume is assumed to occur by horizontal expansion. If at the original level I the pressure was $p_1$ and the temperature $T_1$, and at the level II 1 gkm. higher the corresponding quantities were $p_2$ and $T_2$, an area of 1 $cm.^2$ at level I, will be increased to $\frac{p_1 \cdot T_2}{p_2 \cdot T_1}$. From this and from the curve showing the amount of vapour per unit volume at various levels, points are obtained showing the remaining amount of water vapour. The difference between the original amount of vapour and the remaining amount after the elevation to a level 1 gkm. higher gives a number of points. A curve through these points shows how much water has been condensed in the air at each level in the elevation of 1 gkm. (Fig. 47 B). From this curve it can be calculated by graphical integration that from the lowest layer, which is 1 gkm. thick, 0.18 g. (1.8 mm.) may be precipitated, while for the four lowest layers, which are one kilometre thick, the figure is 0.48 g. (4.8 mm.). The former corresponds to 30 % and the latter to 85 % of the total amount condensed. From this we see the quantitative significance of the lowest layers in precipitation formation.

The question now arises of the amount of water to be found on the 22nd. in that part of the warm-sector air which, according to trajectories, caused the precipitation from upward gliding air in Scandinavia and Finland. In order to obtain a value exceeding the real value we have included the warm-sector as far down as 51° N. We suppose that the warm-sector is of a size at ground level indicated by the ground chart and that the boundary zone between warm air and cold air has such a slope that the increase in the area of the warm-sector is proportional to the height. In the calculation the warm-front surface has been assumed to have the smallest slope that seems possible with regard to observations in the upper air.

We have also assumed that the wet-bulb potential temperature everywhere has the value 8°. Actually this value is only exceeded in the southern parts at levels higher than 4 gkm., and these have no significant influence on the calculated amount, as the temperature values have everywhere else been lower, and considerably so in the lower rain-giving layers. Moreover, the air is far from saturated with vapour in the layers where the wet-bulb potential temperature exceeds the value 8°. The relative humidity at Hamburg, for instance, is only 50 %. The amount of water there is thus still less than has been assumed in the calculation.

In the calculation we have also assumed that the ground level pressure is 1 000 mb. As a rule the value is lower, and hence the real quantity of vapour is still less than the calculated value.

Our assumptions have thus been such that the calculated amount of vapour certainly exceeds the real amount.

The quantity of vapour above the warm-sector is directly obtained as the product of the area and the calculated amount 1.8 g. in a vertical pillar of cross-section 1 cm². The quantity of vapour above the sloping front-surface is obtained in the following way. From the above-mentioned curve for the variation of the quantity of vapour with height (Fig. 48 A) we calculate by integration the total amount of vapour existing above ground level, above 1 gkm., above 2 gkm. and so on. The values thus obtained are plotted on

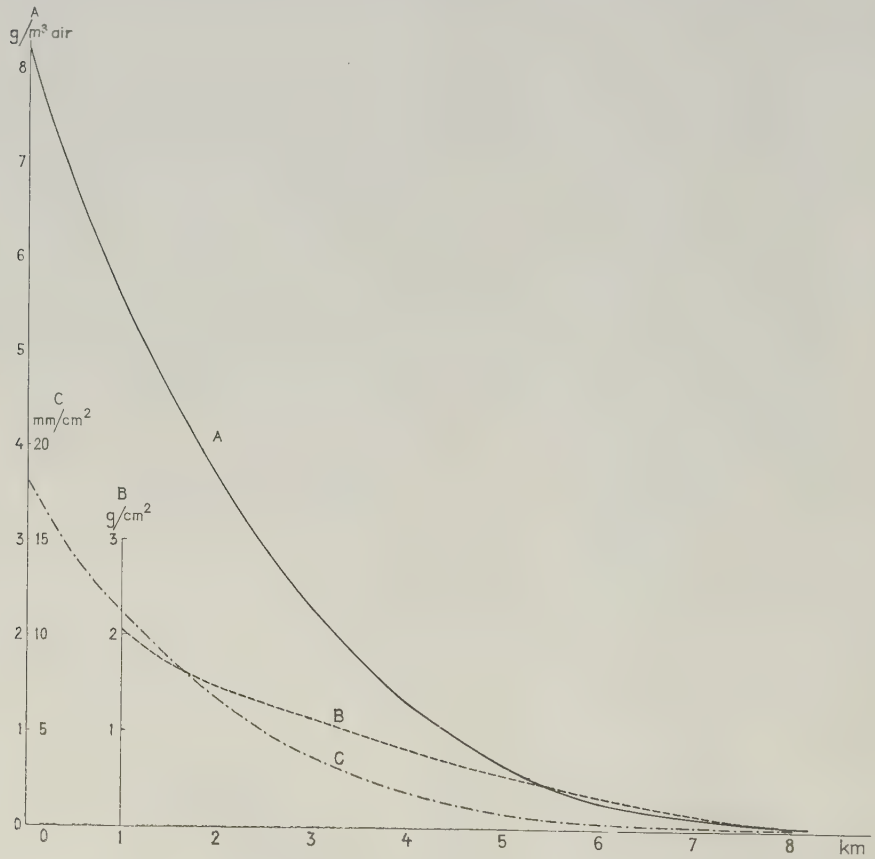



Fig. 47. A) Variation with height of the amount of water vapour, expressed in grams pr m.³ of saturated air. — B) The amount of water in g./cm.³ air condensed when the same air mass is elevated through 1 gkm. — C) The total quantity of water vapour in grams contained in an air pillar of base 1 cm.² when the height of the base above sea level variers.
The air in A), B) and C) is assumed to be saturated with water and to have a wet-bulb potential temperature of 8° at all levels.

a graph and the curve $f(z) = F(S)$ (Fig. 47 C) is drawn. The total quantity of vapour above the front surface is, when $S_0$ is the area of the warm sector at the ground and $S_z$ that at the level $z$.

$$I = \int_{S_0}^{S_z} F(S)\, dS$$

According to the assumptions made, $S_z - S_0 = K \cdot z$,

$$I = K \int_0^z f(z)\, dz$$

$K$ is obtained from the chart for 500 mb. from which the area $S_z$ and the height $z$ can easily be calculated.

$\int_0^\infty f(z)\, dz$ is calculated by integration from the graph (Fig. 47 C).

According to calculations the quantity of vapour above the warm-sector amounts to $324 \cdot 10^{13}$ g. and the quantity above the front-surface is the same, the total being $648 \cdot 10^{13}$ g.

The comparison between the calculated precipitated water amount, $768 \cdot 10^{13}$ g., and the vapour amount in the warm air before condensation, $648 \cdot 10^{13}$ g., shows that more water has been precipitated than that to be found in the warm air. Let us emphasise that in the calculations such assumptions have consistently been made that the calculated initial quantity in the warm air is greater than the real quantity, whereas the calculated precipitated quantity is less than in reality.

It is also to be noted that in the occlusion a quantity of warm air flows from the low-pressure area owing to divergence, so that the total humidity there cannot have been precipitated. Thus we reach the same conclusion as in studying trajectories and wet-bulb potential temperatures, namely that some of the precipitation has been caused by the elevation of originally cold air, since considerably more water has fallen as precipitation from upward gliding air within the cyclone than previously existed in the warm air.

One might expect that the air on the 22nd. at 0700 hours GMT contained, in addition to vapour, so much water in liquid form that the greater part of the precipitation originated from this. However, the character of the precipitation and the extension of the clouds, as they were observed from the ground and from aeroplanes over large areas of the warm air, indicate that this may have been the case only to a very small extent. Thus, in view of the work of Hann-Süring (1939) and p. 25 above, we assume that the quantity of liquid water is small compared with the quantity of vapour. Moreover, we find that the air on the 24th. at 0700 hours GMT still contained much moisture and that water was still precipitated. From the above discussion we see that it is especially in the later period of the cyclone that cold air contributes to precipitation.

Let us attempt to make a general summing-up of the history of the cyclone. It was formed in a pressure field favourable to frontogenesis at ground level. No upper fronts

could be observed, and they probably did not exist. There was, however, quite a powerful solenoid field. By circulation, fronts were formed in certain parts of the low-pressure area (Kjeller). To start with the warm air consisted of two separate air masses; one was true tropical air at high levels and one had been carried round the high-pressure area over England and had only been moderately heated. The warm air laying higher up was carried out of the cyclone by the divergence of the wind to the right in relation to the gradient wind. The rising air current also continued after the occlusion, and the rising air was to an increasing extent original cold air, which was warm in relation to the newer cold air.

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The low-pressure area over Iceland of the 23rd. now has its centre over Scotland. The ground chart gives an unclear warm-front with an apparent upward gliding motion

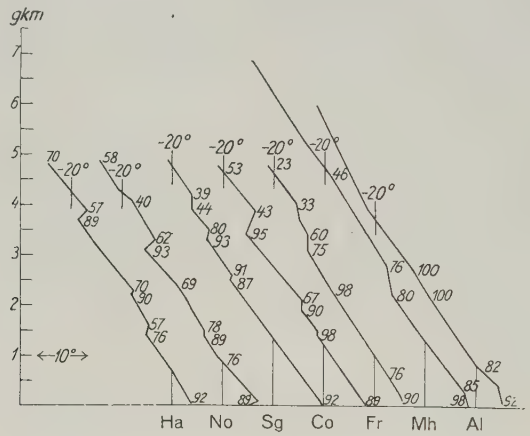


Fig. 48. Some temperature-height diagrams on April 24th. Hamburg, Norderney, Soesterberg, Cologne, Frankfurt, Mildenhall and Aldergrove.

in the rain area and drizzle in the warm-sector, as well as a comparatively well developed cold-front. The soundings show that the structure of the disturbance in many ways deviates from the cyclone pattern.

We have four soundings in the district before the ground warm-front (see Fig. 48), Hamburg, Nordeney, Cologne and Frankfurt. Hamburg shows several small inversions with decreasing humidity. Between 3 100 and 3 700 gm. there is a layer of »nässender As» at a temperature of — 15.2° to —18.7°. The stratification is moist-indifferent in this layer and slight ice formation is reported. Nordeney, which lies near the ground cold-front, shows a similar stratification. The cloud formation is less distinct and above 3 300 gm. there is a powerful subsidence and dry air. At Cologne moist-lability prevails up to 2 000 gm. and above this there is a layer of clouds, 10/10 As, at 2 900—3 400 gm. with moist-indifference and moderate ice formation and finally, above this, dry air.

At Frankfurt moist-lability also prevails above 2 000 gm. and at greater heights the air becomes increasingly dry and hardly any clouds are visible. Soesterberg and Mildenhall lie within the warm-sector. They both have high values for the wet-bulb potential temperature at ground level and these values decrease with height up to approx. 3 300 gm. at Soesterberg and 2 000 gm. at Mildenhall (see Fig. 49). As the air is very moist up to these levels, this implies that the stratification is unstable. No front with upward gliding can be found (see Fig. 49). All the layers within which the wet-bulb potential temperature rapidly increases are associated with a marked decrease in humidity. If there is an upward gliding motion at all it must be limited to the lower layers below 3 500 gm. We have previously discussed whether a certain precipitation could not be

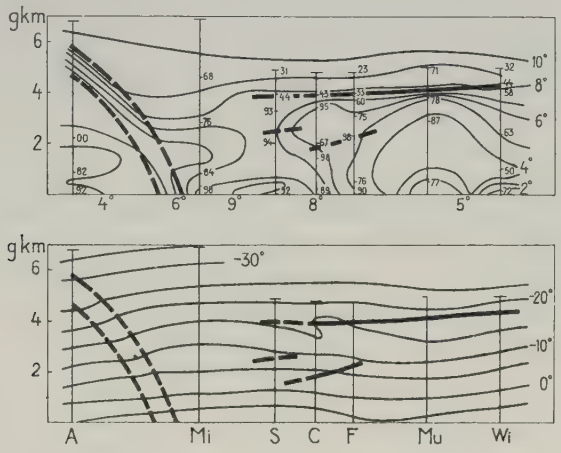


Fig. 49. Vertical sections showing the temperature (C) and wet-bulb potential temperature on April 24th. Aldergrove, Mildenhall, Soesterberg, Cologne, Frankfurt, Munich and Vienna.

explained with the aid of the conception of over-running cold air. In the discussion, however, no definite conclusion has been reached, on account of the difficulty of taking into consideration the size of the downward motion of cold air at high levels. In the present case we have a similar phenomenon, which might be interpreted as »underrunning warm air». From the ground chart and the height-chart at 700 mb. it is clear that the warm-air advection over Hamburg at 500 gm., where the value of the gradient wind from the ground chart is assumed to apply, is approximately twice as large as at 700 mb. Without vertical motions such an advection must within six hours cause a labilisation of the air below 700 mb. We might imagine, in this case also, that a vertical motion could prevent labilisation by subsidence at high levels, but on the other hand labile layers already exist, and it seems more probable that these layers were formed by advective processes than by general elevation and vertical stretching.

## Conclusion.

The aim of this investigation has been to increase our knowledge of atmospheric circulation to the extent that this has been possible with the material available. Many problems have thus been treated, some of necessity rather superficially and others more extensively. Exact methods have been used in examining the material, in calculating the courses of isotherms and isogeopotentials inside and in the proximity of fronts, and in certain other cases. When using the material for the study of air motions, the displacements and changes of fronts and air masses and other phenomena connected with changes in the atmosphere, exact results cannot as a rule be obtained. By critically examining the instruments and observations, and discussing the weather conditions, the author has tried to show the relative probabilities of different interpretations.

The question also arises, to what extent the results may be generalised. Generalisations should be the aim of the synoptic weather service, which has very little time at its disposal in which to consider and carefully examine material. Nevertheless, in scientific treatment of synoptic material generalisations must be made with caution. To the extent that previous results are reached again, a certain general application may be regarded as proved, and this is of course also true if the same phenomenon has been observed on several occasions during the period investigated here. Other results which have not previously been found, and in certain ways contradict the prevailing ideas, may be suspected of being completely exceptional or at least less usual. Only by a series of futur investigations can these questions definitely be settled.

In the introduction the development of synoptic meteorology has been briefly touched upon and an account of serial ascents and previous aerological investigations has been given.

A report has been made of the material used and this has been critically examined. In this connection systematical errors such as lag errors, radiation errors and speed errors have been discussed, and in certain cases corrections have been made. In cases where chance errors or systematical errors in pressure or temperature have occurred, which can be assumed to have been constant during the whole sounding, we have given a method for correction (see Table IV, p. 12).

The construction of height-charts has been treated, and special consideration has been given to the drawing of isogeopotentials and isotherms near and inside fronts and frontal zones. We have found a tendency to an anticyclonic curvature of the relative isogeopotential lines above the ground fronts and to a cyclonic curvature of these lines in the fronts at high levels (see Fig. 3 a). The course of an absolute isogeopotential line is shown in Fig. 3 b. The number of isotherms in a front is calculated in the following manner. Through extrapolation of the temperature-height curve from the lower boundary of a front to the level of the upper boundary of this front we obtain a temperature value. The difference between this temperature value and the actual temperature at the upper level of the front gives only a part of the total number of isotherms in the front. The

other part is the horizontal temperature fall outside the front in a region as wide as the front (see Fig. 2, p. 17).

An attempt has been made to follow air currents at high levels by studying the trajectories which were obtained from the gradient wind, and at the same time by studying wet-bulb potential temperatures, the mixing ratio and the quantity of precipitation.

The construction of cross-sections has been treated, in connection wherewith the errors have been discussed which, on account of advective processes, have been caused by using time-sections instead of space-sections.

A short account has been given on the drawing of synoptic ground charts as well as a summary of synoptic conditions for each day at 0700 hours GMT. The detailed synoptic-aerological description has been made chronologically; in each chapter the situation has been treated for one day together with the development during the previous 24 hours. Among the results achieved by the synoptic analysis there are many that confirm results obtained in previous investigations. Here we will only mention some of these.

1. On the 18th., 20th., 21st., and 24th. April distinct tropopause depressions are observed over Scandinavia in which the tropopause is considerably lower than in the surroundings, not only in the south but also in the north, which shows that in addition to advection a downward vertical motion in the tropopause region must have taken place.

2. On April 21st. at Stockholm the tropopause is as far down as 5.47 gkm., and at the same time multiple tropopauses are observed.

3. On April 18th. a powerful *north-west* wind in the higher levels of the atmosphere poured in warm air over western Europe.

4. The current above the warm-front surface is anticyclonic, and that above the cold-front surface is cyclonic.

5. On several occasions, as on the 18th., 19th., and 22nd. April, the situation can be interpreted in the following manner: Tropical air first enters at 7 to 9 gkm., that in the stratosphere progressing in the manner of a cold-front.

6. The slopes of the fronts are as a rule 1/100 for the warm-front and 1/50 for the cold-front.

7. In the distinct fronts on the 18th. and 19th. April the value of the wet-bulb potential temperature in the fronts only increased insignificantly with the height.

8. The value of the wet-bulb potential temperature in well developed fronts diminishes towards the north by about 5° per 1 000 km., which corresponds to the conditions within the high-pressure area whence the warm air has come.

9. The temperature differences at 300 mb. are less than those at higher and lower levels.

The deficiencies of the data regarding the density of observations in time and space and also regarding the reliability of the observations make it necessary to present new results with reservations. We will not repeat these reservations in detail, but will present

in brief the more important results which the author considers should be accepted, or which may serve as a guide in forthcoming investigations based on future material which may be expected to be superior in all respects to that used in this investigation. The present material is, however, on account of its extent in space, superior to that upon which previous synoptic-aerological investigations have been based.

1. The existence of distinct fronts also at higher air levels is in many cases undeniable, but there is good reason to believe that their existence is neither a necessary nor a sufficient condition for cyclogenesis or for the formation of cyclonic rain areas.

2. The analysis of the wave disturbance above Central Europe on the 17th. shows that the disturbance was free of fronts at high levels and was formed in a frontal zone 1 000 km. wide, embracing approx. 10°. Apparently the precipitation was caused by an elevation of parts of the baroclinic air mass, but it is not completely out of the question that cold air running ahead at high levels may have contributed to the precipitation.

3. In a second wave disturbance above the Atlantic, west of Scotland, on the 21st., no distinct fronts appear to have existed to start with. These were kinematically formed, however, in certain parts of the cyclone by circulation in a strongly baroclinic district similar to the area in which the wave disturbance of the 17th. was observed.

The former of these wave disturbances appeared in an area where the inclination of the tropopause was greater than usual. Otherwise the difference between the two cases, as far as can be ascertained from the data, is that the air pressure of the 21st. appears to rise in the western part of the disturbance so that the circulation is favoured by it. This initial rise of pressure seems less to be conditioned by the actual cyclogenesis than by a factor independent thereof.

4. On the 21st.—22nd. a front was formed at the cyclogenesis above Scotland and the North Sea. Other front-formations or reinforced fronts could be observed on the 18th. and 19th. above the North Atlantic. On the 21st.—23rd. previously observed fronts completely vanished while new ones were formed within the same disturbance area.

5. The question of rapidly moving cold air at high levels, which causes moist-lability, has been discussed for the 17th. and 18th., and we believe that it is a not unusual phenomenon, causing precipitation, which when judged exclusively by ground observations may be regarded as rain from upward gliding air. A corresponding phenomenon, when the warm-air advection at ground level was greater than at high levels, resulting in a similar appearance of moist-lability, occurred on the 24th. in Western Germany.

6. In an occluded cyclone we very often find from the ground observations an extremely distinct »upper cold-front» and a ground warm-front. These were also possible to detect on the 23rd. and 24th. in the cyclone over Scandinavia, although the aerological material in no way supported such an interpretation.

7. It is striking how precipitation, and together with it the apparent fronts, tend to adjust themselves to the prevailing pressure and pressure tendency. Thus on the 20th. typical precipitation from upward gliding air occurred along an »occlusion front» which extended approx. 1 000 km. directly northward from Leningrad. The thermal significance

of this front is unclear. It is certain that it did not originate in a simple occlusion process. In the north it was surrounded by air masses quite different than those further to the south; and the air mass which in the north caused precipitation has completely different thermal properties from those of the mass to the south, which gave similar precipitation. The pressure distribution and its changes are intimately connected with the height variation of the tropopause. A fall-area at ground level is related to a fall of the tropopause, and a rise at ground level with a rise of the tropopause.

8. In cyclones a transformation of warm air occurs by the occlusion process, according to the scheme **T→P**, during the elevation. On the 23rd. and 24th. April the cyclone continues, whilst forming precipitation, to elevate air (**P**) which at first appeared in the cyclone as cold air, but which is warm in relation to the later introduced cold air. As fronts are absent one may speak in this connection of a continuous regeneration of the cyclone.

9. While in the cyclones the transformation **T→P** takes place, the opposite transformation **P→T** occurs in the sub-tropical high-pressure areas. In regions between high-pressure areas and low-pressure areas the transition occurs gradually. The cold air, which on the 17th. and 18th. of April flowed down over Central Europe, and on the 20th. was secluded in South Russia and in the Balkans on account of the rapid progress of warm air at 55° N in Central Russia, retained its cold-air properties fairly unchanged until the 22nd. when the pressure began to rise and subsidence started, after which it was rapidly transformed.

10. The conception of air masses as an aid to analysis must be used with caution when aerological measurements are lacking. The transformation of an air mass is a process which is extremely difficult to follow from the ground and which, as has been pointed out, may be very slow. By way of example it may be stated that the air mass, originally **P**, which on the 17th. poured down over Western Central Europe, flowed round the high-pressure area above Southern England, and after four days and nights appeared as warm air in the wave disturbance north-west of Scotland. In the course of this the value of the wet-bulb potential temperature only rose by approx. 2°. In cases when aerological measurements are available the air mass is usually more readily characterised by its measured qualities than by patterns, which may easily be misleading.

11. The air above a cold-front on the 22nd. of April, which, with regard to previously used terms, should have been called cold tropical air, appears to have nothing in common with tropical air, but should be termed polar air, which after falling (free Föhn) becomes considerably warmer than the cold air coming more directly from the north at ground level.

12. The air current does not follow the gradient wind. An attempt has been made to calculate the deviation from the gradient wind for April 22nd. and a deviation has thus been found indicating an escape from the cyclone, which is deepened, towards a high-pressure area nearby. This deviation was observed at the 800 to 500 mb. level, but may have reached higher levels.

13. Air must flow out of the cyclone, and the wind at certain levels must have

a component from the fall area, as the fall centre has a relatively small inclination in relation to the vertical.

14. The development of fall and rise areas and their depth at ground level as well as aloft shows that in the cyclogenesis above Scotland and the North Sea on the 21 th. the air in large districts, beyond those covered by the chart, must have taken part. We see here an example of what world-wide processes the changes of weather are and what a large extension of the aerological net is necessary in order that the causes of these changes may be examined. A corresponding increase in the intensity of observations in time and space is just as necessary when we aim at an accurate knowledge of the weather.

15. The quantity of vapour in a cyclone has been calculated under certain assumptions. The significance of the lowest layers of air in the formation of precipitation has been quantitatively demonstrated. When a moist air-pillar is elevated through 1 gkm., 30 % of the condensed water is provided by the layer 1 km. thick, nearest the ground, and 85 % by the layer 4 km. thick nearest the ground.

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